Optimum Divergence of the Transmitter Optical Radiation in FSO Systems

Tsvetan Mitsev[1], Nikolai Kolev[2], Hristo Ivanov[3] and Kalin Dimitrov[4]

Abstract – **The determination of the optimum divergence of the transmitter optical beam $\theta_{t,opt}$ in FSO systems can largely compensate for the negative impact of the change in the direction of propagation of the optical radiation due to various random factors. Depending on the system parameters, the length of the communication channel and the typical weather working conditions, the proper choice of θ_t can significantly increase the reliability of information transmission and reduce the probability of outage. In this paper the influence of the optical output power of the transmitter and the length of the communication channel on the value of optimum divergence of the laser beam after the transmitting antenna are shown. When the divergence of the transmitter beam is set, the FSO system of TU-Sofia can work reliably under conditions where the deviations of the beam from its main direction exceed more than twice the deviations in the absence of adjustment.**

Keywords – **Communications, Free Space Optics, Laser Beam, Diverging Angle, Beam Wander**

I. INTRODUCTION

The application of FSO systems is becoming more and more frequent with specific connection conditions in the contemporary communication systems and networks. This is due to their wide bandwidth, tight radiation pattern of antenna, small size and weight, lower price, license free frequency band, that is, no frequency planning is necessary. The increased interest in FSO systems, however, creates new requirements for improvement of their characteristics, as well as for optimizing some of their parameters, in particular those of the divergence of the transmitter optical radiation [1-4].

One of the reasons for decreasing the functioning reliability of FSO systems are the random angle fluctuations of the transmitter laser beam from the direction where the receiver is placed. The main reasons for their existence are the turbulent fluctuations in the atmosphere and the mechanical movements of the bases on which the transmitter/receiver sets are placed (or building sway) [5-7]. The phenomena mentioned have coherent action in order to decrease the connection channel length or increase the outage in case of poor weather conditions. A typical way of overcoming this problem is the use of redundant power with a perfect optical setting of the system and when there is a possibility that there are only geometrical losses, which we have considered in our paper [1]. In it, we have derived an expression for calculating the maximum radial displacement of the receiver antenna center from the transmitter laser beam axis, depending on the initial Gaussian beam radius.

This paper is a continuation of [1]. We have proven the significance of a transmitter optical antenna with adjustable angle width of the transmitter diagram in order to increase the functioning reliability of the system. We have researched the impact of the optical radiation source power and the connection channel length on the value of the optimum divergence angle of the transmitter optical radiation. We have indicated the basic parameters of the system and the connection channel.

II. OPTICAL PROPAGATION AND INTENSITY DISTRIBUTION. DEFINITION OF THE PROBLEM

In the selected location of the FSO system and a perfect optical setting, that is a coincidence of the optical antennae axes of the opposite transmitter/receiver sets, angle $\theta = 0$. The *BER* value with a perfect setting usually reaches values lower than 10^{-20}, when the values for normal functioning of the FSO systems are within the range of 10^{-12} to 10^{-8}. This allows, when the source power remains the same, for an increase of the divergence of the transmitter θ_t, and in this case there is an increase in the value of the maximum acceptable angle deviations θ_{max} of the laser beam from its main direction when the condition is fulfilled that the received power Φ_r is bigger than the threshold value $\Phi_{r,\,min}$, respectively the minimal average radiation intensity in the receiver aperture I_r is bigger than $I_{r,\,min}$ (fig.1). With the further increasing of θ_t we reach the maximum value of θ_{max} when the installation and parameters of the system are fixed, and then θ_{max} starts decreasing and we derive $\Phi_r < \Phi_{r,\,min}$, including the case where the angle is $\theta = 0$.

As it is evident fig.1, for the derivation of the optimum laser beam divergence of the transmitter $\theta_{t,\,opt}$, where on certain conditions we derive the maximum value of θ_{max}, we need an intensity distribution model of the light of the source in the receiver antenna plane. This means that at a distance z from the transmitter in a plane transverse to the distribution with a assumption for azimuthally beam symmetry, we have to derive the radial distribution of the plane density of the power $I(\rho, z) \equiv I(\theta, z)$. This distribution depends mainly on the

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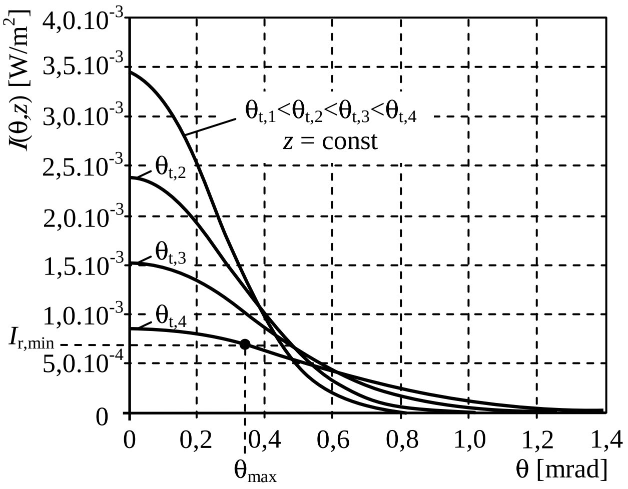

Fig.1. Dependence of the radial distribution of intensity of optical radiation $I(\theta, z)$ in the plane of the receiver (z = const) at different divergences of the transmitter optical radiation θ_t (θ_{max} is the maximum acceptable angular variance of transmitter's beam from its main direction in case of $\theta_{t,4}$).

phase and amplitude distribution of the field in the emitting aperture $A_t = \pi R_t^2$. R_t is the aperture radius of the transmitting antenna. In our model we will use synchronous phase and Gaussian amplitude distribution in the emitting aperture [1], [8]. The maximum intensity value is along the beam axis, respectively in the center of the emitting aperture. When $\rho = \rho_0$, the light intensity decreases by e^2 in relation to the maximum and ρ_0 is defined as an initial Gaussian beam radius. In order to keep the Gaussian radial distribution in the Fraunhofer zone

$$z \geq z_{c,\,exp} \tag{1}$$

it is necessary to fulfill the condition

$$R_t \geq 2\rho_0 \, . \tag{2}$$

$z_{c,\,exp}$ is calculated by the formula

$$z_{c,exp} = \frac{10\rho_0^2}{K_\theta \lambda_0}\,, \tag{3}$$

where λ_0 is the central wavelength of the light source,

$$\rho_0 = \frac{K_\theta \lambda_0}{\pi \theta_{t,exp}}\,, \tag{4}$$

and K_θ is the coefficient indicating the random fluctuations of the field phase in A_t. These fluctuations are due to different stochastic factors in the laser generation, and these factors worsen the radiation coherence level and lead to a difference between the actual divergence and the theoretically defined one $\theta_{t,\,teor}$,

$$\theta_{t,exp} = K_\theta \theta_{t,teor}\,, \tag{5}$$

and typically $K_\theta \geq 10$.

When the conditions (1) and (2) are fulfilled, the current Gaussian radius is calculated by the formula

$$\rho_z(z) = \sqrt{\rho_0^2 + \left(\theta_{t,exp} z\right)^2} \tag{6}$$

and

$$I(\rho_z, z) = I(0,z).\mathrm{e}^{-2}$$

is fulfilled.

The losses in the light distribution between the transmitter and the receiver when there is a assumption of an uniform volume extinction coefficient α_e, are calculated by the formula

$$\tau_a = e^{-\alpha_e z}\,,$$

$$\alpha_e\left[\mathrm{km}^{-1}\right] = \frac{3{,}92}{S_M\,[\mathrm{km}]}\left(\frac{\lambda[\mu\mathrm{m}]}{0{,}55}\right)^{-q}. \tag{7}$$

In (7) τ_a is the transparence of the connection channel, S_M is the meteorological visibility of the atmosphere, and for the typical atmospheric conditions the exponent q is calculated by the formula

$$q = 0{,}585\sqrt[3]{S_M\,[\mathrm{km}]}\,.$$

With the assumptions made, the optical radiation intensity along the optical axis and its radial distribution are

$$I(0,z) = \frac{2\tau_t \tau_a(\lambda_0, S_M, z)\Phi_L}{\pi\rho_z^2(z)}\,,$$

$$I(\rho,z) \equiv I(\theta,z) = I(0,z).\mathrm{e}^{-2\left(\frac{\theta}{\theta_{t,exp}}\right)^2}. \tag{8}$$

In (8) the losses in the transmitter antenna optics have been expressed by τ_t, Φ_L is the power of the source radiation, θ is the angle deviation of the transmitter optical beam axis, recognized from the case of perfect alignment, that is coincidence of the optical axes of the transmitter and opposite receiver optical antenna. The power Φ_L is the laser power with a assumption for a digital communication system with On/Off modulation (OOK) in the optical code impulse.

With the digital communication systems with OOK modulation, the system functioning quality is guaranteed by the low values of *BER*. With them, we calculate *BER* from *SNR* again using an erfc function, which presupposes a great slope in the changing of *BER*. A change by one order of *SNR* leads to a change up to ten orders of *BER*. Because of that it is more convenient to deal with and to represent graphically the change of *SNR* from the different parameters of the system. To calculate *SNR* we need the optical beams at the input of the receiver. The optical beam through the input aperture of the receiver corresponding to the upper level of the optical code impulse, is

$$\Phi_{\mathrm{pd}}(\theta,z)=\pi.\tau_{\mathrm{r}}.R_{\mathrm{r}}^{2}.I(\theta,z). \qquad (9)$$

In (9) R_r is the aperture radius of the receiver telescope, τ_r is the transmission coefficient of the optical receiver system. The above equation is true when the condition $\rho_z(z) >> R_r$ is fulfilled.

The second in significance input optical beam, that is the background one, is calculated by the formula

$$\Phi_{\mathrm{B}}=\pi^{2}\tau_{\mathrm{r}}L_{\lambda,\mathrm{B}}(\lambda_0)R_{\mathrm{r}}^{2}\theta_{\mathrm{r,exp}}^{2}\Delta\lambda_{\mathrm{F}}, \qquad (10)$$

where $L_{\lambda,\mathrm{B}}$ is the spectral brightness of the background radiation, and $\Delta\lambda_F$ is the transmission wavelength bandwith of the interference filter before the photodetector, placed to restrict the background radiation.

With the indication of the dispersion of the two main types of noise in the optical receivers, the thermal and the quantum one, the expression for *SNR* calculation is

$$SNR=\frac{R_{\mathrm{I}}(\lambda_0)\,\Phi_{\mathrm{pd}}(\theta,z)}{\sqrt{C_{\mathrm{I}}\left\{\dfrac{2k_{\mathrm{B}}T.A}{R_{\mathrm{Fb}}}+eR_{\mathrm{I}}(\lambda_0)\left[\Phi_{\mathrm{pd}}(\theta,z)+\Phi_{\mathrm{B}}\right]\right\}}}.(11)$$

The formula is true for an optical receiver with preamplification and a p – i – n photodiode.

$R_{\mathrm{I}}(\lambda_0)=8{,}06.10^{5}\,\eta(\lambda_0)\lambda_0$ is the integral sensitivity for current of the photodetector, $\eta(\lambda_0)$ is the quantum efficiency of the photodetector material, k_B is the Boltzmann constant, e is the charge of the electron, C_I is the information throughput of the digital communication system, and R_{Fb} is the value of the resistor in the feedback of the preamplifier.

III. SIMULATION RESULTS AND DISCUSSIONS

For the developed and implemented in TU-Sofia FSO system [9], [10] we will determine the maximum divergence $\theta_{t,\,opt}$ of the transmitter optical beam. The system works at a wavelength λ_0 = 850 nm with information throughput C_I = 100 Mbps with power in the optical bit impulse Φ_L = 10 mW. Using a two-lens Kepler collimator, we gradually change the beam divergence within the range of 1 mrad to 5 mrad. The connection channel length is up to 2 km. The other system parameters necessary for the calculation using the method developed in II, are: τ_t = 0,85; K_θ = 10; R_r = 5,5 cm; θ_r = 5 mrad; τ_r = 0,85; $\eta(\lambda_0)$ = 0,7; $\Delta\lambda_F$ = 10 nm; R_{Fb} = 1 kΩ; A = 5. For the calculations we choose values S_M = 10 km, $L_{\lambda,B} = 10^{-2}$ W/m^2.sr.Å, T = 300 K, and the constants are $k_B = 1{,}38.10^{-23}$ J/K, $e = 1{,}602.10^{-19}$ C.

In fig.2, with an increasing divergence $\theta_{t,\,exp}$ of the transmitter beam, we have shown the dependence *SNR*(θ). It is evident that, when we choose a minimal level for the signal/noise ratio SNR_{th} = 11,2, which corresponds to $BER \approx 10^{-8}$, the maximum possible divergence of the beam θ_{max} from the perfect alignment increases with the increasing of θ_t in the beginning, and then it starts decreasing, as we have already predicted.

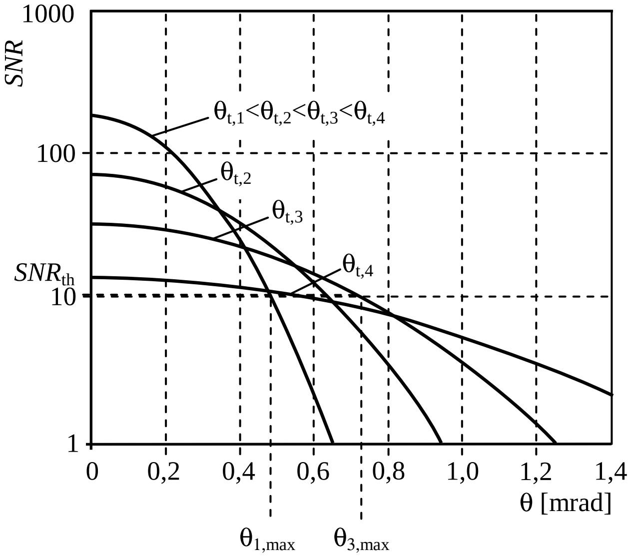

Fig.2. Dependence of the signal to noise ratio from angular deviation θ of the beam of the transmitter from its main direction at different divergence of transmitter optical radiation θ_t.

The dependence $\theta_{max}(\theta_t)$ for three values of the optical radiation source power Φ_L = [10, 15, 20] mW with connection channel length z = 2 km has been shown in fig.3. It is evident that when the power Φ_L increases, θ_{max} increases, too. From the graphics it is evident that if we want to have the maximum value of θ_{max}, it is necessary to change θ_t too, this means that its optimum value exists and it is $\theta_{t,\,opt}$. When Φ_L increases two times and with an optimum value of the transmitter optical beam divergence, the maximum possible angle beam divergence increases by 37%. It is also evident

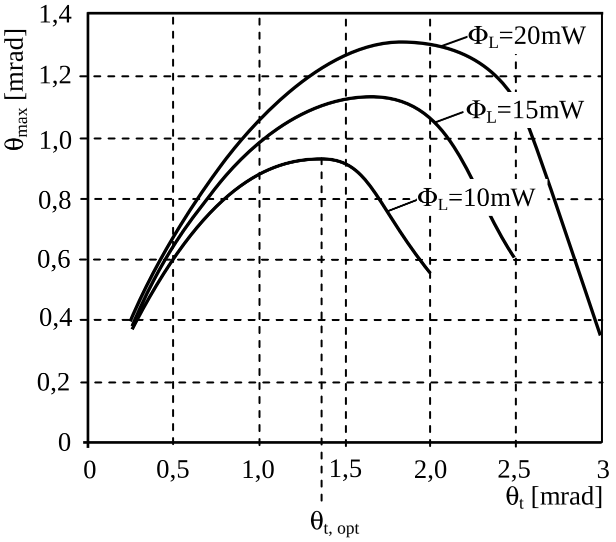

Fig.3. Dependence $\theta_{max}(\theta_t)$ at z = 2 km for three values of Φ_L. Determination of $\theta_{t,\,opt}$ (Φ_L = 10 mW).

from the graphics that θ_{max}, depending on Φ_L, undergoes more significant changes with the great values of θ_t.

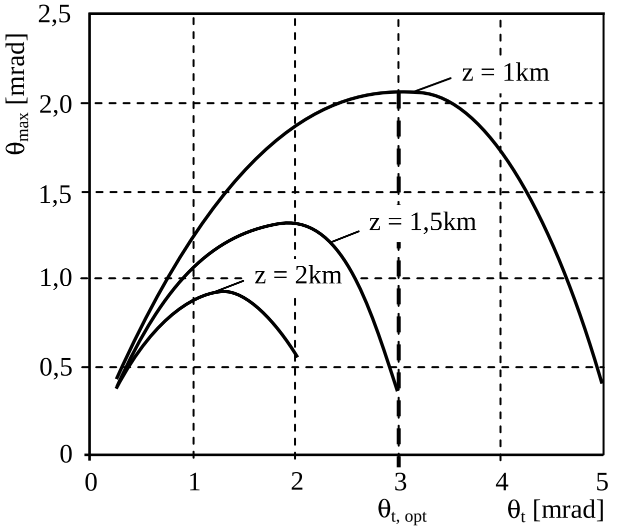

Fig.4. Dependence $\theta_{max}(\theta_t)$ at Φ_L = 10mW for three values of z. Determination of $\theta_{t,opt}$(z = 1 km).

In fig.4 is shown the dependence $\theta_{max}(\theta_t)$ for three connection channel lengths *z* = [1, 1,5, 2] km when the optical radiation source power is Φ_L = 10 mW. With the decreasing of the distance *z* is necessary a significant readjustment of the transmitter optical system, but as a result we can achieve a significant improvement of the functioning abilities of the system. When *z* is decreased 2 times, it is necessary to increase θ_t by almost 3 times in order to maintain the optimum setting of the system. As a result, however, the possibilities of divergence of the beam from the main direction and keeping the functioning of the system, are more than 2,2 times greater.

In the comparisons between fig.3 and fig.4 it is evident that the functioning of the system is more sensitive to the change in the connection channel length that it is to the optical radiation source power. When the values of the optical radiation divergence are $\theta_t < 1$ mrad, the impact of the changing of *z* or of Φ_L on θ_{max} can be ignored.

IV. CONCLUSION

This paper shows the possibility of a significant increase in the functioning and reliability of an FSO system with an optimum optical radiation divergence setting of the transmitter $\theta_{t,\,opt}$. Its value depends on the particular parameters of the system and the communication channel. We have researched the impact of the connection channel length *z* and the power in the code impulse of the optical radiation of the source Φ_L on the maximum possible divergence θ_{max} of the transmitter beam from the perfect direction, that is when there is a location on single optical axis of the opposite transmitter/receiver antennae $\theta = 0$ (fig.2). We have shown that the values $\theta_{max}(\theta_{t,\,opt})$ increase when Φ_L increases and they decrease when *z* increases, and the connection channel length *z* has a greater impact on them. When there is a constant collimation of the transmitter beam, that is a constant value θ_t, the value of θ_{max} is influenced to a much greater extent by *z* and Φ_L when the values of θ_t are big than when they are small, for instance when $\theta_t \leq 1$ mrad. When there is an optimum beam divergence setting, within the limits of the research defined (III) it is possible to have a 121% increase in the acceptable value of the divergence θ_{max}.

ACKNOWLEDGEMENT

This work has been supported by the Research Programme of the Technical University of Sofia, Bulgaria, Internal Projects 2011, contract Nb 112pd033-07.

REFERENCES

[1] Ts. Mitsev, K. Dimitrov, B. Bonev, “Influence of Laser Beam Divergency on Free Space Optic Systems Functionality”, TELECOM’2008, Conf. Proc., Varna, Bulgaria, 2008.

[2] Zh. Zhao, R. Liao, Y. Zhang, “Impact of Laser Beam Deverging Angle on Free-Space Optical Communications”, Aerospace Conference, IEEE, pp. 1-10, 2011.

[3] A. Farid, S. Hranilovic, “Outage Capacity Optimization for Free-Space Optical Links with Pointing Errors”, Journal of Lightwave Technology, Vol. 25, Issue 7, pp. 1702-1710, 2007.

[4] Y. Ren, A. Dang, B. Luo, H. Guo, „Capacities for Long-Distance Free-Space Optics Links Under Beam Wander Effects“, Photonics Technology Letters, IEEE, vol. 22, issue 14, pp. 1069-1071, 2010.

[5] Shlomi Arnon, “Effects of Atmospheric Turbulence and Building Sway on Optical Wireless Communication Systems”, Opt. Lett., vol. 28, No. 2, pp. 129-131, 2003.

[6] E. Ferdinandov, B. Pachedjieva, B. Bonev, Sl. Saparev, “Joint Influence of Heterogeneous Stochastic Factors on Bit-Error Rate of Ground-to-Ground Free-Space Laser Communication Systems”, Optics Communications, vol. 270, issue 2, pp. 121-127, 2007.

[7] Bonev B., Relative Influence of Some Stochastic Factors on Bit-Error Rate of Ground-to-Ground Free Space Optics, ICEST 2007, Vol. 1, pp. 203-206, Ohrid, Macedonia, 2007.

[8] E. Ferdinandov, B. Pachedjieva, K. Dimitrov, Optical Communication Systems, Sofia, Technika, 2007.

[9] Ts. Mitsev, N. Kolev, K. Dimitrov, “Optical Wireless Communication System”, XII-th International Scientific Conference SMOLJAN-2010, Smoljan, Bulgaria, 26-27 June 2010.

[10] N. Kolev, “Selection of optimal settings depending on the FSO system parameters", XIII International PhD Workshop OWD 2011, Conf. Proc., vol. 29, pp. 467-472, Warsaw, 2011.