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# Availability of Free-Space Optical Systems Depending on Atmospheric Conditions and System Parameters

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**ABSTRACT**

In this paper the availability of Free-Space Optical (FSO) systems is studied. In order to create mathematical model and calculate systems availability, meteorological data from different geographic regions is used to obtain statistical model of the atmospheric visibility $S_M$. Utilizing the cumulative distribution functions (*CDF*) of $S_M$ and the statistical distribution of the misalignments ($\Delta\rho$) between the laser beam axis and the center of the receiving antenna, a method for calculating FSO availability is proposed. Based on the derived analytical expressions, numerical results are obtained and FSO availability is analyzed.

**Key words:** FSO, availability, CDF, beam divergence.

## 1. INTRODUCTION

The commercialization of FSO systems in the past years necessitates the improvement of their channel capacity and reliable work (availability). This poses the question for selecting the optimal parameters of the free-space optical communication system [1]. One of the causes for the decrease of the FSO reliability is the random shifts of the laser beam axis from its original direction. These misalignments can be caused by mechanical vibrations of the transmitting aperture [2, 3], strong atmospheric turbulence [4] or pointing errors [8]. They can significantly reduce the quality of the transmitted data and the FSO availability. Another factor for unreliable work of the FSO system is the atmospheric visibility $S_M$ [9]. Significant decrease of $S_M$ can cause system outage.

The remainder of this paper is paper is organized as follows: Section 2 describes the factors that may cause random fluctuations in the laser beam direction; Section 3 presents the problem, which is solved in this study. In Section 4 the models for calculating the minimal optical power in the photodetector, the optimal beam divergence angle (Section 4.1), the atmospheric visibility (Section 4.2), the random vibration in the optical beam direction (Section 4.3) and the availability (Section 4.4) are presented. Section 5 contains the numerical simulations and Section 6 is the conclusion.

## 2. REASONS FOR RANDOM FLUCTUATIONS OF THE LASER BEAM DIRECTION

Some of the main reasons for linear displacements ($\Delta\rho$) of the optical beam from its original direction are:
- Mechanical vibrations of the transmitter, caused by instability of the foundation, where FSO transceiver is mounted [13, 14] (FSO is located on vibrating platforms within industrial warehouses, near production sites, etc.)
- Building sway (when the FSO system is located on top of very high buildings)
- Turbulent eddies [8, 12]

The first two cases are identical. Mechanical vibrations in the transmitter's side cause a linear shift in the direction of the optical beam. The jitter in the direction of the laser beam propagation triggered by atmospheric turbulence is more complex physical process [4]. It is caused by the largest turbulence eddies, which sizes $l \sim L_0$ ($l_0$ is the inner scale size of the turbulent eddies and $L_0$ is the outer scale size) are proportional to the distance between the transmitter and the receiver.

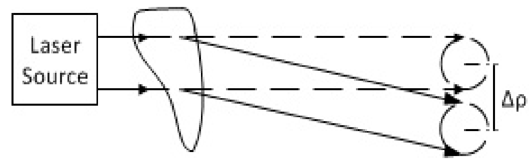



**Figure 1:** Change of the laser beam direction caused by turbulent eddies

However, no matter the cause of the misalignment, it results in a linear shift $\Delta\rho$, between the center of the receiving aperture and the optical beam axis (Figure 1). So it can be generalized as a jitter in the initial direction of the laser beam propagation.

When the transmitting aperture (TA) is shifted in any direction with a random angle $\gamma$ (Figure 2), the receiving aperture (RA), with radius $R_r$, is displaced from the axis z of the optical beam. This misalignment $\Delta\rho$ is also random, because, when $z = Z$:

$$\Delta\rho = \gamma Z \qquad (1)$$

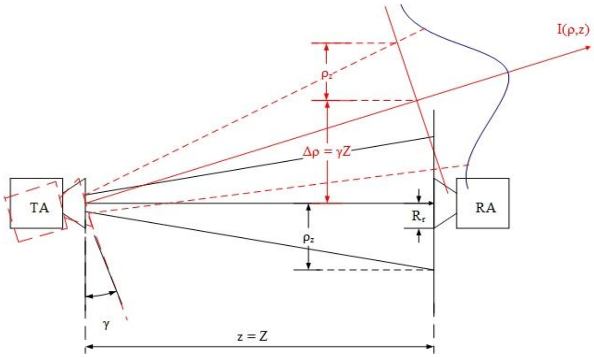



**Figure 2:** Misalignment between the center of the receiving aperture and optical beam axis

In Figure 2 $\rho_z$ is the radius of the optical beam at the plane of the receiver, which is defined by $I(0, z)/e^2$. Optical radiation intensity along the beam axis is $I(0, z)$.

## 3. DEFINING THE PROBLEM

Commercially available systems work with collimated optical beams. As a result there is a very high reserve of optical energy at the receiving end of the system, which leads to FSO working with very low bit error rates (BER < $10^{-20}$). Afore mentioned conditions (see Section 2) can cause misalignments between the laser beam axis and the center of the receiving aperture. This means that working with collimated laser beam increases the probability for system outage, caused by unbearable jitter in the direction of the laser radiation. The great reserve of optical energy, when using non-divergent optical beams provides the possibility to enlarge the divergence angle of the optical beam and therefore its radius $\rho_z$ at the plane of the receiving aperture [7, 10]. The larger beam radius at the receiver's side allows for greater linear misalignments between the center of the receiving aperture and the optical radiation axis. This lowers of fully eliminates the probability of outage caused by random fluctuations in the initial direction of the laser beam. The FSO parameters, which can be manipulated until achieving their optimal values are: beam divergence angle, and respectively, laser beam radius.

Consider the case shown in Figure 3. It depicts the radial distribution of the optical radiation intensity in the plane of the receiver's aperture $I(\rho, z)$. The intensity $I_{min}$ corresponds to the minimum optical power through the aperture of the receiver, for which FSO system will work reliably. The respective magnitude of the beam radius $\rho_{max}$ defines the angle $\theta_{max}$. This is the value of bearable angular misalignment (the respective maximal linear misalignment is $\rho_{max}$) of the laser beam axis from its main direction ($\theta = 0$) due to different random factors. The divergence angle of the optical radiation is represented with $\theta_t$.

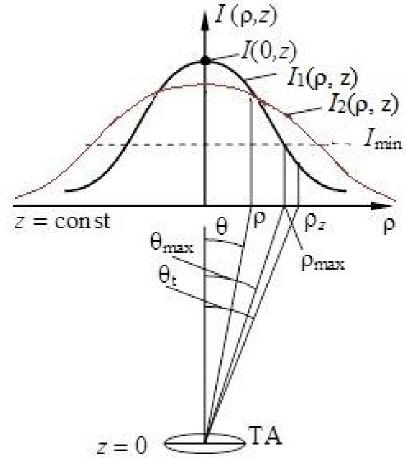



**Figure 3:** Distribution of the optical intensity at the plane of the receiver

In Figure 3 two distributions of $I(\rho, z)$ are represented with $I_1(\rho, z)$ and $I_2(\rho, z)$, respectively. They correspond to two divergence angles $\theta_{t,1}$ and $\theta_{t,2}$ ($\theta_{t,1} < \theta_{t,2}$) of the transmitted laser beam. The figure outlines the case of $\theta_{max}(\theta_{t,1}) \geq \theta_{max}(\theta_{t,2})$, but it is obvious that this trend will continue to the limit value $\theta_{t,opt}$. After this point, increasing $\theta_t$ will result in decrement in the magnitude of $\theta_{max}$. The task of the following analysis is to calculate $\theta_{t,opt}$, and to investigate the availability of FSO system working with this optimal value of the beam divergence angle.

## 4. MATHEMATICAL DESCRIPTION

### 4.1. Calculation of the Minimal Optical Power in the Photodetector and the Optimal Beam Divergence Angle

The filed distribution at receiver's site, as shown in Figure 3, is Gaussian [5, 11], therefore

$$I(\rho,z) = I(0,z)\exp\left(-2\frac{\rho^2}{\rho_z^2(z)}\right) \tag{2}$$

When $\theta_t$ is optimal, the effective radius is equal to the maximal linear misalignments ($\rho = \rho_{max}$) and field intensity is minimal $I = I_{min}$, i.e.

$$I_{min} = I(0,z)\exp\left(-2\frac{\rho_{max}^2}{\rho_z^2(z)}\right) \tag{3}$$

Optical radiation intensity along the axis of the laser beam depends on the characteristics of the transmitter and the atmospheric communication channel [1]:

$$I(0,z) = \frac{2.\tau_t.\tau_a(\lambda_0, S_M, z).\Phi_L}{\pi.\rho_z^2(z)} \tag{4}$$

where $\tau_t$ represents the losses in the receiving antenna and $\tau_a$ is the transparency of the atmospheric channel. The power of the transmitted laser beam is $\Phi_L$.

From (3) and (4) the expression for $\rho_{max}$ can be derived:

$$\rho_{max} = \frac{1}{\sqrt{2}}\rho_z\sqrt{\ln\frac{2.\tau_t.\tau_a.\Phi_L}{\pi.\rho_z^2.(1-e^{-2})I_{min}}}, \tag{5}$$

where $e = 2.7182$

The value of the beam radius $\rho_z$, which allows the extreme magnitude of $\rho_{max}$ is

$$\rho_z \equiv \rho_{z,opt} = \sqrt{\frac{2.\tau_t.\tau_a.\Phi_L}{\pi.e.I_{min}}} \quad (6)$$

$I_{min}$ can be calculated from the condition

$$I_{min} = \frac{\Phi_{pd}\big|_{SNR=const}}{\pi.\tau_r.R_r^2} \quad (7)$$

When SNR value is given, $\Phi_{pd}$ is calculated from the bellow expression [3]:

$$SNR = \frac{R_I.\Phi_{pd}}{\sqrt{C_I\left[\frac{2.k_B.T.A}{R_{Fb}} + e^{-}.R_I.\left(\Phi_{pd} + \Phi_B\right)\right]}}, \quad (8)$$

where $R_r$ is the integral sensitivity of the photodetector:

$$R_I(\lambda_0) = 8{,}06.10^5\eta(\lambda_0)\lambda_0 \quad (9)$$

From (8) and physical considerations, the following expression for optical signal flux at the entrance of the photodetector is reached

$$\Phi_{pd} = \frac{1}{2}\left[\frac{SNR^2.C_I.e^{-}}{R_I} + \left(\left(-\frac{SNR^2.C_I.e^{-}}{R_I}\right)^2 + \frac{4SNR^2.C_I}{R_I}\left(\frac{2k_B.T.A}{R_I.R_{Fb}} + e^{-}.\Phi_B\right)\right)^{\frac{1}{2}}\right] \quad (10)$$

Background optical flux $\Phi_B$ is calculated using the equation

$$\Phi_B = \pi^2.\tau_r.L_{\lambda,B}.R_r^2.\theta_r^2.\Delta\lambda_F \quad (11)$$

Optimal value of the beam divergence angle is

$$\theta_{t,opt} = \frac{\rho_{z,opt}}{Z}, \ [rad] \quad (12)$$

Considering formulas (6) through (12) the final expression for $\theta_{t,\,opt}$ is reached

$$\theta_{t,opt} = \frac{1}{Z}\sqrt{\frac{2\tau_t\tau_a\tau_r R_r^2\Phi_L}{e\Phi_{PD}\big|_{SNR=const}}} \quad (13)$$

### 4.2. Statistical Model of the Atmospheric Visibility

Real yearly measurements of the atmospheric visibility [9] were used for creating this generalized version of the statistical model of atmospheric visibility.

The steps for the generalization of the measured data are:
- Calculating the arithmetic mean value of each $P(S_M \geq S_{M,\,min})$
- Calculate the standard deviation σ for the given statistical data
- For each $S_M \geq S_{M,\,min}$ set the interval [x – σ; x + σ], where $x \equiv S_M$.
- Plot the results as a graphic and approximate the resulting curves using the simple trend line tool

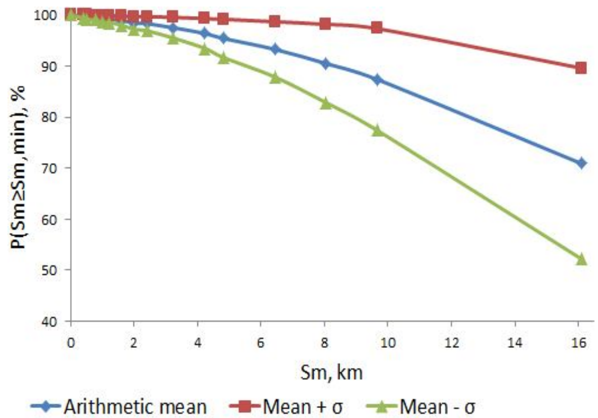



**Figure 4:** Generalized model of the atmospheric visibility

The equations, which approximate the tree models for $P(S_M \geq S_{M,\,min})$ illustrated in figure 4, are:

- worst case “Mean - σ”:

$$P(S_M \geq S_{M,\,min}) = 0.00004\ x^3 - 0.0019\ x^2 - 0.0077\ x + 0.9972 \quad (14)$$

- arithmetic mean:

$$P(S_M \geq S_{M,min}) = 0.0000006x^4 - 0.00001x^3 - 0.0007x^2 - 0.0053x + 0.9991 \quad (15)$$

- best case “Mean + σ”:

$$P(S_M \geq S_{M,min}) = -0.0005x^2 + 0.0016x + 0.9975 \quad (16)$$

For a complete statistical model, the cumulative distribution function (*CDF*) and the probability density function (*pdf*) of $S_M$ are needed. By definition *CDF* is equal to the probability $P(S_M \leq S_{M,\,min})$, which means:

$$CDF = P(S_M \leq S_{M,min}) = 1 - P(S_M \geq S_{M,min}) \quad (17)$$

Also

$$P(S_M \leq S_{M,min}) = \int_0^{S_{M,min}} f(S_{M,min})dS_M \quad (18)$$

The probability density function $f(S_M)$ for each statistical model (arithmetic mean, mean + σ and mean – σ) is equal to

$$f(S_M) = \frac{dP(S_M \leq S_{M,min})}{dS_M} \quad (19)$$

Having all the functions $P(S_M \geq S_{M,\,min})$, $CDF(S_M)$ and $f(S_M)$ defined, the statistical model for the atmospheric visibility is completed. In the remainder of this paper the polynomial representing the arithmetic mean, (15), will be used as a model for $P(S_M \geq S_{M,\,min})$.

### 4.3. Statistical Model of the Random Vibrations in the Initial Direction of the Optical Beam

In order to define a model for FSO availability, it is also needed to have the model of the random jitter in the initial direction of the laser beam axis.

Consider the case illustrated in Figure 2. Having no statistical data in the literature, it is practical to assume a Gaussian distribution of the angular misalignments $\gamma$ ($\gamma_{max} \equiv \theta_{max}$) of the optical beam axis from its original direction [2, 12]. Taking into account (1), it can be concluded that the linear displacements $\Delta\rho$ in the plane $z = Z$ are also normally distributed:

$$f(\Delta\rho) = \frac{1}{\sqrt{2\pi}\sigma_{\Delta\rho}} \exp\left(-\frac{\Delta\rho^2}{\sigma^2_{\Delta\rho}}\right) \quad (20)$$

Also

$$\sigma^2_{\Delta\rho} = Z^2\sigma^2_{\gamma} \quad (21)$$

The cumulative distribution function is

$$CDF = F(\rho_{max}) = \int_{-\infty}^{\rho_{max}} f(\Delta\rho)d\Delta\rho = \\ = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\Delta\rho}{\sqrt{2}\sigma_{\Delta\rho}}\right)\right] \quad (22)$$

### 4.4. Mathematical Model of FSO System Availability

In order to have an FSO system working reliably, it is required that the power of the optical radiation, at the receiver's site (plane $z = Z$), is greater than or equal to the minimal acceptable power, so $I(\rho, z) \geq I_{min}$ [1].
FSO will be in outage if:
1). $S_M$ falls below a critical value $S_{M,\,min}$, according to which the system parameters are calculated,
Or
2) The linear misalignments $\Delta\rho$ exceed the maximal acceptable value $\rho_{max}$, calculated using (5).

Condition 1 says that the probability for reliable work of the FSO system is $P(S_M \geq S_{M,\,min})$ [1], which was already defined in equations (14) through (16).

Condition 2 means that FSO will work reliably if the random linear shifts in the direction of the optical radiation are less than $\rho_{max}$ ($\Delta\rho \leq \rho_{max}$). So the reliable work of FSO, depending on $\Delta\rho$ is defined by

$$\int_{\rho'_{max}}^{\rho_{max}} f(\Delta\rho)d\Delta\rho = 2\int_{0}^{\rho_{max}} f(\Delta\rho)d\Delta\rho = \\ = 2(F(\rho_{max}) - F(0)) \quad (23)$$

Where $F(\Delta\rho)$ is the cumulative distribution function of the linear misalignments (22) and $\rho'_{max}$ is equivalent to $|-\rho_{max}|$. Considering 1) and 2), Availability is equal to the joint probability

$$Availability = \\ = P(S_M \geq S_{M,min}; \rho'_{max} \leq \Delta\rho \leq \rho_{max}) \quad (24)$$

Knowing that $f(S_M)$ and $f(\Delta\rho)$ are independent the above equation is equal to [6]:

$$P(S_M \geq S_{M,\,min}; \rho'_{max} \leq \Delta\rho \leq \rho_{max}) = \\ = \int_{S_{M,\,min}}^{\infty} \int_{\rho'_{max}}^{\rho_{max}} f(S_M; \Delta\rho)\, dS_M\, d\Delta\rho = \\ = 2\int_{S_{M,\,min}}^{\infty} f(S_M)dS_M \int_{0}^{\rho_{max}} f(\Delta\rho)\,d\Delta\rho = \\ = 2P(S_M \geq S_{M,v\min})P(0 \leq \Delta\rho \leq \rho_{max}) \quad (25)$$

The needed system parameters are calculated as defined in (4) through (12).

Using equations (14) through (19) and (23) through (25), a simple analytical expression for FSO availability is derived:

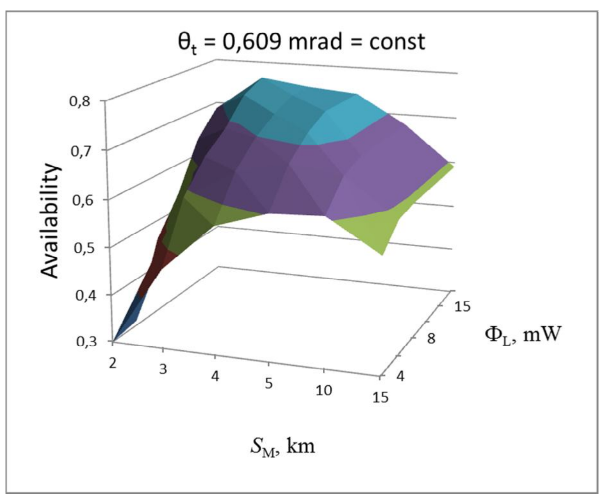
$$Availability = \\ = 2(F(\rho_{max}) - F(0))P(S_M \geq S_{M,min}) \quad (26)$$

The system reliability calculated using the above formula will give the percentage of time, during which the system will work correctly using the calculated optimal system parameters.

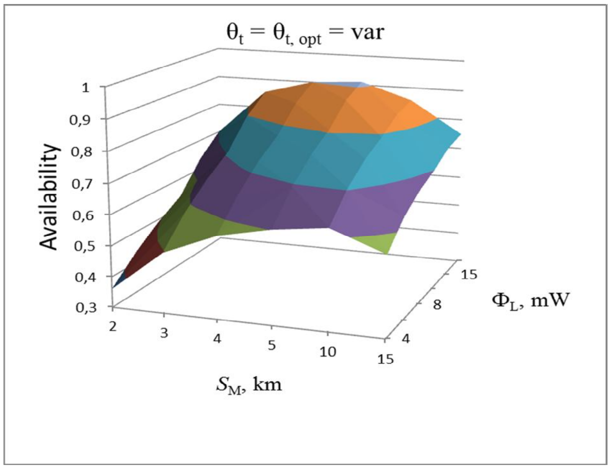
## 5. SIMULATION RESULTS

In order to calculate FSO availability, the following typical system parameters were used: channel capacity, $C_I$ = 1 Gbps; quantum efficiency of the photodetector material $\eta(\lambda_0)$ = 0,7; $SNR$ = 11,2 (corresponds to BER=$10^{-8}$);central wavelength $\lambda_0$ = 1,55 µm; T = 300 K; aperture coefficient A = 5; value of the resistor in the feedback of the preamplifier, $R_{Fb}$ = 1 kΩ; $\tau_r = \tau_t$ = 0,85; $R_r$ = 5,5 cm; transmission wavelength of the interference filter before the photodetector $\Delta_{\lambda F}$ = 10 nm; background radiation, $L_{\lambda,B}$ = $10^{-2}$ W/m2.sr.Ång (corresponds to bright day); angular width of the receiving antenna $\theta_r$ = 5 mrad

Figure 5 shows the availability of FSO system using fixed $\theta_t$ (Figure 5a), and variable beam divergence angle $\theta_t = \theta_{t,opt}$ = var (Figure 5b).




a)



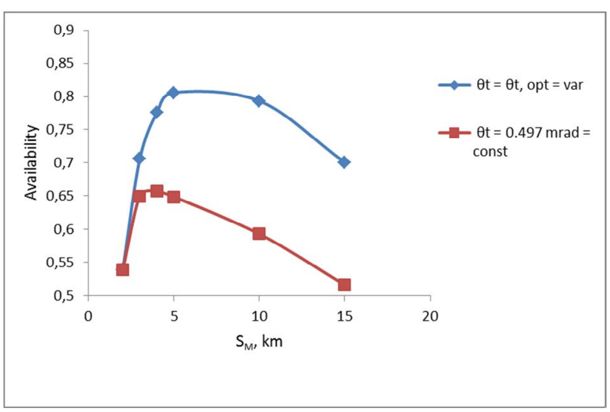

b)

**Figure 5:** Availability of FSO system using a) fixed beam divergence angle and b) optimal beam divergence angle. $S_M$= var, $\Phi_L$ = var, $z$ = 2 km

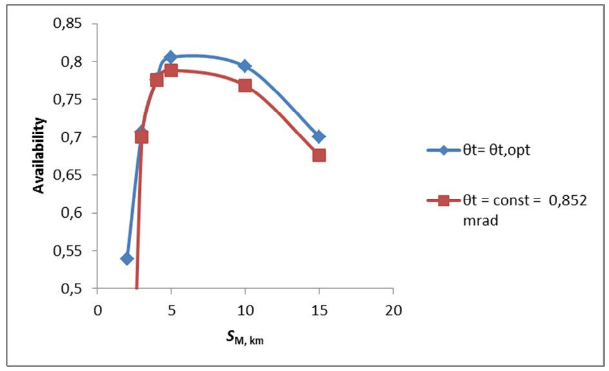
The figures 5a) and 5b) represent the percentage of time, in which the system will work reliably with optimal system parameters calculated according to the variable $S_M$ and $\Phi_L$. It is observed that there is about 10 to 20 % gain in the system availability, if working with optimal value of $\theta_t$.

Figure 6 a) through Figure 6 c) show a comparison between the availability of FSO using $\theta_t = \theta_{t,opt}$ = var and a system that uses a constant beam divergence angle. Simulations are performed for various atmospheric conditions (different $S_M$).

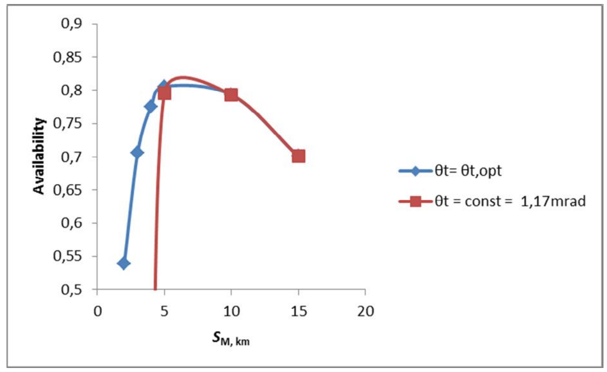
It is observed that in all cases using optimal beam divergence angle result in higher availability. However the results presented in Figure 6 a) through c) also show that when using collimated beam constantly (Figure 6 a)) the FSO availability is much lower compared to using $\theta_t = \theta_{t,opt}$. This is because non-divergent optical beams allow minimal shifts between optical beam direction and the center of the receiving aperture; availability is reduced, because there is higher probability of having $\Delta\rho \geq \rho max$.




a)



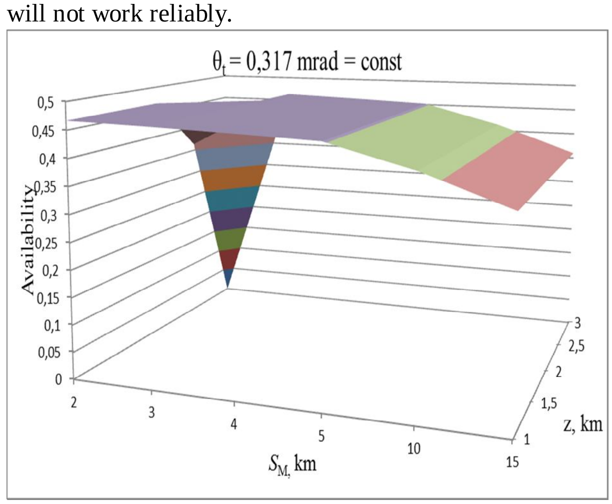

b)



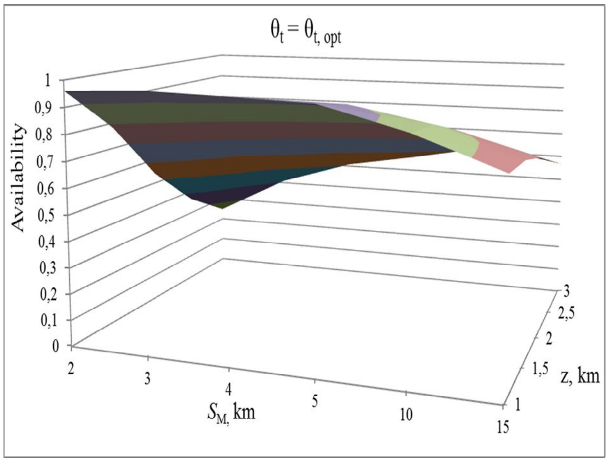

c)

**Figure 6:** Comparison between FSO using different fixed beam divergence angles and FSO using $\theta_t = \theta_{t,opt}$ = var

On the other hand, when using larger fixed values of $\theta_t$, availability is closer to optimal case (difference is about 4%), but this is valid only when atmospheric conditions are good ($S_M \geq 5$ km). When the transparency of the atmosphere in the communication channel drops the system will not work reliably.




a)




b)

**Figure 7**: Availability of FSO system using: a) fixed beam divergence angle; b) optimal beam divergence angle ($S_M$= var, z = var, $\Phi_L$ = 10 mW)

Figure 7 presents the change in FSO availability under different atmospheric conditions and different lengths of the communication channel (the distance between transmitter and receiver). The results confirm the previous findings that using collimated optical beam (with fixed beam divergence angle) results in lower FSO availability compared to using FSO capable to keep beam divergence angle to its optimal value ($\theta_t = \theta_{t,opt}$ = var).

Figure 8 shows FSO system availability when different receiving antennas are used, calculations of FSO availability are performed for $\theta_t = \theta_{t,opt}$ and assuming that there is a jitter in the direction of the optical beam propagation.

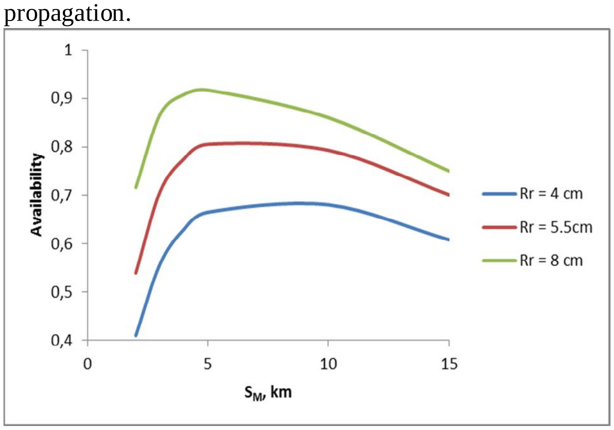



**Figure 8**: Availability of FSO system using optimal beam divergence angle, when different receiving apertures are used (z = 2 km, $\Phi_L$ = 10 mW)

System parameters are calculated using equations (5) through (13). Availability is calculated as defined in (26). As expected, when smaller apertures are used system availability is lower. This is because using smaller receiving aperture requires more optical power at the plane of the receiver $z = Z$, which means that working with smaller beam divergence angle $\theta_t$ is needed. In this case FSO system availability is reduced because there is higher probability of having unbearable shifts from the initial direction of the optical beam.

Aperture averaging could be used to further improve the system performance (this optimization is not analyzed in the paper). Antennas with larger radiuses can also be utilized to minimize the impact of the scintillation within the optical beam, caused by atmospheric turbulence.

The outage probability of FSO system can easily be calculated as (1 – Availability). This is the amount of time the system will work unreliably.

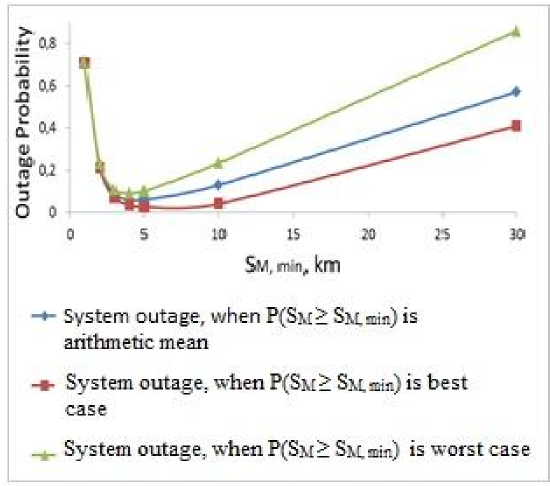



**Figure 9**: Outage probability of FSO system using optimal value of $\theta_t$ and z = 2km, $\Phi_L$ = 10 mW

Figure 9 depicts the outage probability of FSO system working with optimal value of $\theta_t$ and in the presence of random jitter in the direction of the optical beam propagation. Calculations are performed, considering the three models of $S_M$ ((14) through (16)), presented in Figure 4. It is observed that, when atmospheric visibility is low and system is working with smaller values of $\theta_{t,\,opt}$ as calculated from (13), the outage probability is high, because there is higher probability of having $\Delta\rho \geq \rho_{max.}$ On the other hand, when transparency of the atmospheric channel is higher, FSO works with wider beam divergence angles. In this case there is a higher probability for system outage due to unbearable decrease of the atmospheric visibility $S_M$.

## 6. CONCLUSION

In this paper a generalized statistical model for atmospheric visibility was presented. A mathematical model for evaluating the FSO systems availability was proposed. Using that model the availability of FSOs with different system parameters was analyzed. A comparison of the availability of FSO system using fixed $\theta_t$ and FSO using $\theta_t = \theta_{t,\,opt}$ was made. Simulations were performed considering different atmospheric conditions. The results clearly show that using optimal values of FSO parameters significantly increases the availability of the system.

The presented models can be used to properly choose FSO parameters (beam divergence angle, channel length, receiver aperture) so that the communication system will work reliably, or they can be used to analyze the availability of a commercial FSO system mounted in a given geographic region (with known atmospheric conditions).

A possible future development of this work is the creation of an algorithm for real time monitoring of the channel parameters, which could be used as a feedback for tuning the system parameters to their optimal values by using adaptive optical terminals. It is expected that this would enable the FSO system to maintain a given BER throughout most of the time, even in poor atmospheric conditions.

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