Impact of Temporary Link Blockage on Ergodic Capacity of FSO System

Milica I. Petkovic and Goran T. Djordjevic

Free-space optical (FSO) systems have attracted much attention from both research and application perspectives owing to their many benefits, such as license-free operation, low-cost, and high data rates. This paper investigates the ergodic capacity of FSO systems, which is an important metric of system performance. The stochastic temporary laser-beam blockage, pointing errors, and atmospheric turbulence are simultaneously considered. The results illustrate that the link blockage causes a decreased ergodic capacity. We show that to maximize the ergodic capacity, there is an optimal value of the laser-beam radius at the waist, which largely depends on pointing errors; however, it is independent of the atmospheric turbulence and the probability of link blockage.

Keywords: Atmospheric turbulence, Ergodic capacity, Free-space optical (FSO) communications, Pointing errors, Temporary link blockage.

I. Introduction

Optical wireless communication (OWC) has been considered as an alternative or complementary to wireless radio-frequency systems. OWC techniques can be applied to applications including short-distance interconnects on integrated circuits, terrestrial point-to-point links and visible light communications, and satellite-to-ground station links and inter-satellite links. Terrestrial free-space optical (FSO) links support high data rates, require a short time for deployment, and are license free. FSO systems can be applied to provide last-mile access or backhaul connectivity. Moreover, FSO technology is suitable for military applications because the transmission of information is very secure. These systems use wavelengths of 800 nm and 1,550 nm, and they convey information over distances of up to several kilometers [1], [2].

1. Literature

As an important metric of the FSO system performance, the channel capacity, which is defined as the maximum data rate that can be transmitted over a channel with an arbitrary small error probability, has been previously analyzed in literature [3]–[13]. When the intensity fluctuations of the received signal are assumed to be very rapid, that is, fading samples at two consequent symbols are independent, the ergodic capacity is a relevant metric. This can be verified by applying an interleaver at the transmitter, and a complementary deinterleaver at the receiver. Some details related to the design of an appropriate interleaver are found in [14]. The expression for the ergodic capacity of an FSO system over a log-normal atmospheric turbulence was derived in [3], while the negative exponential fading statistic was analyzed in

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[4]. The capacity performance of the FSO channel under the strong atmospheric turbulence described by the K distribution is presented in [5], [6]. In [7]–[10], the expression for the ergodic capacity of the FSO channel under the influence of the Gamma-Gamma atmospheric turbulence was derived. In addition to the Gamma-Gamma turbulence, the effect of the pointing errors was analyzed in [10] and [11]. In [11], the ergodic capacity was reported in integral form, while Ref. [10] presented corresponding closed-form expressions in terms of Meijer's G-functions. In [10], the expression for the ergodic capacity was derived under the assumption that the parameter that describes the misalignment fading, denoted here by ξ, is much greater than one. Furthermore, in [12], the ergodic capacity analysis of the FSO link was performed, and considered various atmospheric turbulence models in combination with a nonzero pointing error model. In addition, the ergodic capacity of a mixed radio-frequency/FSO relaying system was observed in [15]–[17].

2. Contribution

In this paper, we derive precise analytical expressions for the ergodic capacity of the FSO link influenced by combined effects of the Gamma-Gamma atmospheric turbulence, pointing errors, and path loss. The novel expression for the ergodic capacity differs from the corresponding result in [10] in the sense that no approximation that is related to the pointing error parameter is introduced here.

In addition, as the main contribution of the paper, the effect of the system failure owing to the stochastic temporary laser beam blockage is considered. The stochastic temporary optical laser beam blockage occurs as a consequence of some random obstacles, such as birds and insects [18]. On the basis of the measured values of the probability of the FSO link blockage presented in [18], the conclusion is that this type of event is not so rare in practice. Derived results are utilized to optimize the beam radius at the waist in order to achieve maximum values of ergodic capacity.

3. Structure

The rest of the paper is organized as follows. Section II describes the system and channel model providing the probability density function (PDF) of the instantaneous signal-to-noise ratio (SNR). Section III presents the ergodic capacity analysis, while the numerical results and discussion are given in Section IV. Some concluding remarks are presented in Section V.

II. PDF of Instantaneous SNR

An FSO that employs intensity modulation/direct detection with on-off keying was considered. The system model is presented in Fig. 1. The information signal is 0 or $2P_t$, where P_t denotes the average transmitted optical power. The received instantaneous SNR is defined as [19, (9)]

$$\gamma = \frac{2P_t^2\eta^2h^2}{\sigma_n^2}, \tag{1}$$

with η denoting the optical-to-electrical conversion coefficient, h is the normalized channel fading coefficient, and σ_n^2 is the power of white Gaussian noise. The received signal intensity fluctuations are caused by the Gamma-Gamma atmospheric turbulence, path loss, and pointing errors. The PDF of the received signal intensity, h, is given by [19, (13)]. Consequently, the PDF of γ is derived as [19, (19)]

$$f_\gamma(\gamma) = \frac{\xi^2}{2\Gamma(\alpha)\Gamma(\beta)\gamma} G_{1,3}^{3,0}\left(\alpha\beta\kappa\sqrt{\frac{\gamma}{\mu}}\middle|\begin{matrix}\xi^2+1\\ \xi^2,\ \alpha,\ \beta\end{matrix}\right), \tag{2}$$

where $G_{p,q}^{m,n}(\cdot)$ denotes the Meijer's G-function [20, (07.34.02.0001.01)] and $\kappa = \xi^2/(\xi^2+1)$. The atmospheric turbulence parameters α and β are determined as [19, (14)]

$$\begin{aligned}\alpha &= \left(\exp\left[0.49\sigma_R^2\Big/\left(1+1.11\sigma_R^{12/5}\right)^{7/6}\right]-1\right)^{-1},\\ \beta &= \left(\exp\left[0.51\sigma_R^2\Big/\left(1+0.69\sigma_R^{12/5}\right)^{5/6}\right]-1\right)^{-1}.\end{aligned} \tag{3}$$

The Rytov variance is denoted as [19, (15)]

$$\sigma_R^2 = 1.23C_n^2k^{7/6}L^{11/6}, \tag{4}$$

where $k = 2\pi/\lambda$ is the wave number, λ is the wavelength, and L is the propagation distance. The refractive index structure parameter, C_n^2, determines the atmospheric turbulence strength.

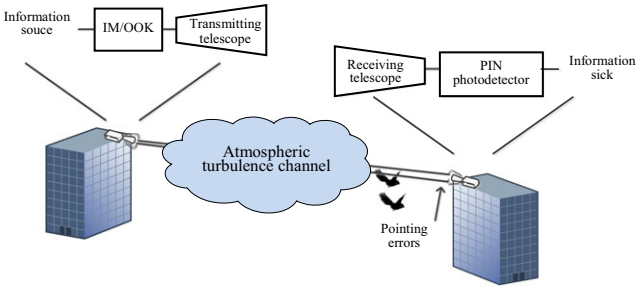

Fig. 1. System model.

The parameter ξ denotes the ratio between the equivalent beam radius at the receiver, z_{Leq}, and the jitter standard deviation, σ_s, as $\xi = z_{Leq}/(2\sigma_s)$. The equivalent beam radius at the receiver is linked to the beam radius at distance L, z_L, as $z_{Leq}^2 = z_L^2\sqrt{\pi}\mathrm{erf}(v)/(2v\exp(-v^2))$, $v = \sqrt{\pi}a/(\sqrt{2}z_L)$, where a is the radius of a circular detector aperture and erf(.) is the error function [20, (06.25.02.0001.01)]. Parameter z_L is related to the beam radius at the waist, z_0, and radius of curvature, F_0, as $z_L = z_0\left((\Theta_o + \Lambda_o)\left(1 + 1.63\sigma_R^{12/5}\Lambda_1\right)\right)^{1/2}$, where $\Theta_o = 1 - L/F_0$, $\Lambda_o = 2L/(kz_0^2)$ and $\Lambda_1 = \Lambda_o/(\Theta_o^2 + \Lambda_o^2)$ [21].

The average electrical SNR is defined as [19, (18)]

$$\mu = \frac{2P_t^2\eta^2\kappa^2A_0^2h_l^2}{\sigma_n^2}, \tag{5}$$

with the atmospheric path loss described by the exponential Beers-Lambert law as $h_l = \exp(-\sigma L)$, where σ denotes the atmospheric attenuation coefficient for clear air terms. The parameter A_0 is the maximal fraction of the collected power, defined as $A_0 = [\mathrm{erf}(v)]^2$, [22].

In addition, optical signal transmission (laser beam) may be interrupted by some kind of moving obstacle coming from the atmospheric surrounding (bird, insect etc.) [18]. If p_s represents the probability of optical signal blockage, the PDF of the instantaneous SNR, γ, is defined as

$$f_N(\gamma) = p_s\delta(\gamma) + (1 - p_s)f_\gamma(\gamma), \tag{6}$$

where $\delta(\cdot)$ is the Dirac delta function [20, (14.03.02.0001.01)].

III. Ergodic Capacity Analysis

If the duration of a symbol is greater than the time over which the channel is significantly correlated, the ergodic capacity is an appropriate measure for FSO system performance, which is defined as [7], [9], [10]

$$C = B\int_0^\infty \log_2(1+\gamma)f_N(\gamma)\mathrm{d}\gamma, \tag{7}$$

where B is the channel bandwidth. By substituting (6) into (7), after applying [20, (14.03.21.0003.01)] as

$$Bp_s\int_0^\infty \log_2(1+\gamma)\delta(\gamma)\mathrm{d}\gamma = Bp_s\log_2(1+0) = 0, \tag{8}$$

and [20, (01.05.26.0002.01)] to represent the logarithm function in terms of Meijer's G-function as

$$\log_2(1+\gamma) = \frac{1}{\ln(2)}G_{2,2}^{1,2}\left(\gamma\middle|\begin{matrix}1, & 1\\ 1, & 0\end{matrix}\right), \tag{9}$$

the ergodic capacity in (7) is re-written as

$$C = B\frac{(1-p_s)\xi^2}{2\ln(2)\Gamma(\alpha)\Gamma(\beta)}\int_0^\infty \gamma^{-1}G_{2,2}^{1,2}\left(\gamma\middle|\begin{matrix}1, & 1\\ 1, & 0\end{matrix}\right) \times G_{1,3}^{3,0}\left(\alpha\beta\kappa\sqrt{\frac{\gamma}{\mu}}\middle|\begin{matrix}\xi^2+1 & \\ \xi^2, & \alpha, \quad \beta\end{matrix}\right)\mathrm{d}\gamma. \tag{10}$$

The integral in (10) is solved using a rule for integrating the product of two Meijer's G-functions given in [20, (07.34.21.0013.01)]. The Meijer's G-function in the obtained expression can be transformed by employing permutations of the parameters using [20, (07.34.04.0003.01), and (07.34.04.0004.01)]. Afterwards, it is simplified by [20, (07.34.03.0002.01)]. The ergodic channel capacity has the final form as

$$C = B\frac{(1-p_s)2^{\alpha+\beta-3}\xi^2}{\pi\ln(2)\Gamma(\alpha)\Gamma(\beta)} \times G_{3,7}^{7,1}\left(\frac{\alpha^2\beta^2\kappa^2}{16\mu}\middle|\begin{matrix}0, & 1, & \frac{\xi^2+2}{2}\\ & & \chi_1\end{matrix}\right), \tag{11}$$

where $\chi_1 = \frac{\xi^2}{2}, \ \frac{\alpha}{2}, \ \frac{\alpha+1}{2}, \ \frac{\beta}{2}, \ \frac{\beta+1}{2}, \ 0, \ 0$. Note that $p_s = 0$ leads to the case when there is no blockage, and the FSO signal transmission will be certainly performed. Otherwise, $p_s = 1$ represents the case when the signal will be definitely blocked, and the transmission will be interrupted. Assuming $p_s = 0$, (11) is an alternative form of the result given in [10, (22)]. Note that the assumption of $\xi^2 \gg 1$ is not utilized as in [10]. A comparison of numerical results that were obtained based on (11) and [10, (22)] will be presented in the next section.

When pointing errors are negligible, the ergodic capacity can be derived by taking the limit of (11) for $\xi^2 \to \infty$. After applying [20, (07.34.25.0007.01), (07.34.25.0006.01) and (06.05.16.0002.01)], the ergodic capacity of the FSO link when intensity fluctuations are caused only by the Gamma-Gamma atmospheric turbulence is derived as

$$C_{GG} = B\frac{(1-p_s)2^{\alpha+\beta-2}}{\pi\ln(2)\Gamma(\alpha)\Gamma(\beta)} \times G_{2,6}^{6,1}\left(\frac{\alpha^2\beta^2}{16\mu}\middle|\begin{matrix}0, & 1 & \\ \frac{\alpha}{2}, & \frac{\alpha+1}{2}, & \frac{\beta}{2}, \quad \frac{\beta+1}{2}, \quad 0, \quad 0\end{matrix}\right). \tag{12}$$

If there is no signal blockage ($p_s = 0$), after using [20, (07.34.16.0001.01)], the convenient alternation is done; therefore, (12) is reduced to the results reported in [7,

(16)], [8, (21)], [9, (10)] [10, (11)]. When parameter $\beta = 1$, the Gamma-Gamma model reduces to the K distribution. Applying [20, (07.34.16.0001.01)] and assuming $\beta = 1$ and $p_s = 0$, (12) comes to [5, (8)].

IV. Numerical Results

This section presents numerical results, which are obtained by using the analytical expression in (11) derived in the previous section. The presented novel analytical expressions for the ergodic channel capacity, which are derived in terms of the Meijer's G-function, can be numerically evaluated using well-known software packages such as Mathematica, Matlab, or Mapple. In addition, Monte Carlo simulations are presented to confirm analytical expressions. Monte Carlo simulations are performed in Matlab on the basis of 10^9 generated samples as follows.

The received signal intensity sample is determined as a product of factors related to the atmospheric turbulence, pointing errors, and path loss, such as, $h = h_a h_p h_l$. The sample h_a represents the random variable related to Gamma-Gamma atmospheric turbulence, which is obtained as $h_a = h_{aX} \times h_{aY}$, where h_{aX} and h_{aY} are mutually independent Gamma random variables modeled by a Gamma distribution. Based on algorithms from [23], [24], random variables h_{aX}, and h_{aX} are generated. The path-loss component h_l is deterministic, and it is calculated based on [19, (12)], [22]. The misalignment fading sample h_p, which is related to pointing errors, is generated based on [22, (9)]. Based on the aforementioned results, the signal intensity sample h can be generated; thus, the SNR sample is generated in a straightforward manner by considering (1) and (6). In our work, the values of p_s are chosen as examples in order to perform the analysis, while some experimental measurements are presented in [18]. In the subsequent analysis, it can be observed that the numerical results are in agreement with the simulation results.

Atmospheric turbulence strength is determined by the refractive index structure parameter as follows: $C_n^2 = 6 \times 10^{-15}$ m$^{-2/3}$ for weak atmospheric turbulence conditions, $C_n^2 = 2 \times 10^{-14}$ m$^{-2/3}$ for moderate atmospheric turbulence conditions, and $C_n^2 = 5 \times 10^{-14}$ m$^{-2/3}$ for strong atmospheric turbulence conditions [19]. The atmospheric attenuation coefficient σ takes a value $\sigma = 0.44$ dB/km, which corresponds to clear-air terms. The wavelength $\lambda = 1{,}550$ nm, noise standard deviation $\sigma_n = 10^{-7}$ A/Hz, and optical-to-electrical conversion coefficient $\eta = 0.8$ are considered. The radius of a circular detector aperture takes a value $a = 5$ cm, while the radius of curvature is $F_0 = -10$ m [19], [21].

Figure 2 presents the dependence of the ergodic capacity on the probability of signal blockage for different values of normalized jitter standard deviation under various atmospheric turbulence conditions. The largest-capacity value exists for $p_s \to 0$, and corresponds to the case when there is no signal blockage. As the value of p_s increases, the ergodic capacity performance worsens. When $p_s = 1$, the laser beam is clearly blocked by some kind of obstacle, which leads to system failure. Under all turbulence conditions and for all values of the normalized jitter standard deviation, the ergodic capacity is relatively constant within the range of blockage probabilities less than 10^{-2}, while the ergodic capacity sharply decreases for blockage probability values greater than 10^{-1}. When the probability of signal blockage is very high, $p_s > 0.7$, and the influence of pointing errors and atmospheric turbulence impairments has less of an impact on system performance.

The dependence of the ergodic capacity on the beam radius at the waist for different values of the normalized jitter standard deviation under various turbulence conditions is presented in Fig. 3. The case when there is no signal blockage is considered ($p_s = 0$), as well as the case when the probability of signal blockage is $p_s = 0.2$. The maximum ergodic capacity corresponds to a specific optimal value of z_0. Hence, the proper selection of the transmitter aperture significantly impacts improvements in the system performance. It should be noted that the value of $z_{0\text{opt}}$ is highly dependent on the normalized jitter standard deviation, while the atmospheric turbulence conditions are of less importance to the value of $z_{0\text{opt}}$. In addition, Fig. 4 shows the ergodic capacity dependence on the beam radius at the waist for different values of p_s. It

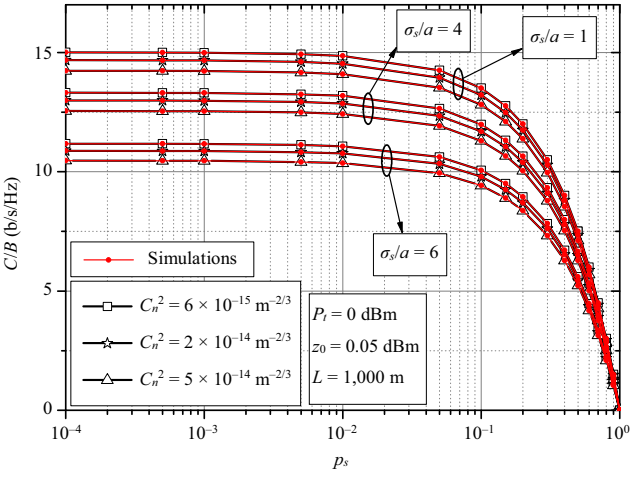

Fig. 2. Normalized ergodic capacity versus probability of blockage.

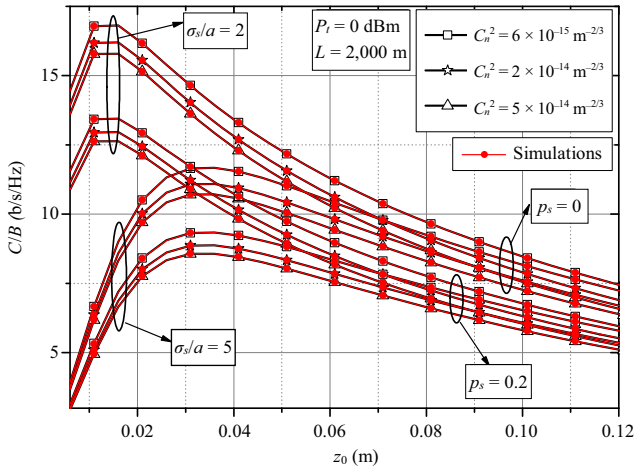

Fig. 3. Normalized ergodic capacity versus beam radius at the waist.

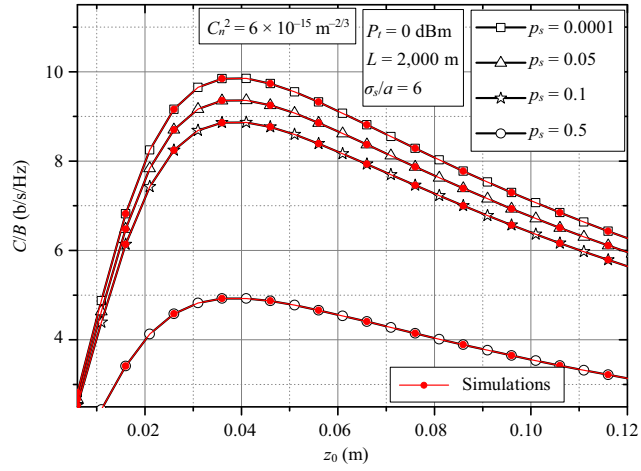

Fig. 4. Normalized ergodic capacity versus beam radius at the waist for different values of probability of signal blockage.

can be concluded that the probability of signal blockage does not influence the optimal value of the beam radius at the waist. In other words, the maximum ergodic capacity is independent of the probability that the signal can be blocked by some kind of obstacle.

Table 1 presents the estimated values of $z_{0\text{opt}}$ for different values of the normalized jitter standard deviation and average transmitted optical power in various

Table 1. Optimum values of the beam radius at the waist $z_{0\text{opt}}$ (cm).

P_t (dBm)	$\sigma_s/a = 2$			$\sigma_s/a = 5$		
	Weak	Moderate	Strong	Weak	Moderate	Strong
–10	1.28	1.27	1.25	2.96	2.91	2.89
10	1.34	1.34	1.34	3.49	3.48	3.47

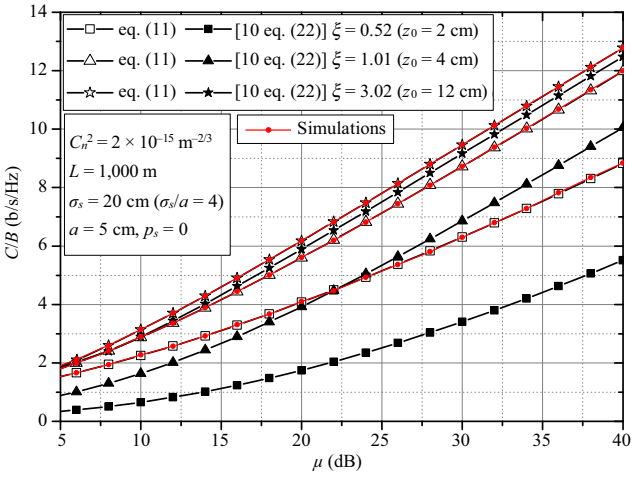

Fig. 5. Normalized ergodic capacity for various degrees of misalignment.

atmospheric turbulence conditions. As already noted, the normalized jitter standard deviation significantly impacts the proper choice of $z_{0\text{opt}}$. As the values of σ_s/a increase, the value of $z_{0\text{opt}}$ increases. Next, lower values of the average transmitted optical power result in smaller values of the beam radius at the waist in order to achieve maximum of ergodic capacity. In addition, poor atmospheric conditions correspond to lower values of $z_{0\text{opt}}$.

Figure 5 presents numerical results based on (11) together with those obtained using [10, (22)]. It is evident that there is a disagreement between the numerical values of the ergodic capacity that are estimated using these two equations. For example, for μ = 30 dB, estimated values of the ergodic capacity corresponding to [10, (22)] and (11) are 3.4 b/s/Hz and 6.3 b/s/Hz, respectively. This disagreement appears to be because [10, (22)] was derived under the assumption of $\xi \gg 1$, which was noted in [10]. As expected, the disagreement between numerical values of the ergodic capacity decreases with increasing values of ξ. A comparison with Monte Carlo simulation shows that the accuracy of (11) is very good, and can be used even for low values of parameter ξ.

V. Conclusions

The main aim of the paper is to investigate the ergodic capacity performance of the FSO system when the stochastic temporary blockage of the laser beam is considered, which occurs as a result of some moving obstacles in atmospheric environments. It has been concluded that the optical beam blockage can lead to significant ergodic capacity performance degradations. In

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addition, the maximization of the ergodic capacity can be achieved by proper selection of the FSO transmitting aperture. It has been noted that the optimal value of the laser beam radius at the waist is highly dependent on the jitter standard deviation. However, the probability of optical beam blockage and atmospheric turbulence conditions have a negligible impact on the optimal value of the laser beam radius at the waist, while a greater average transmitted optical power leads to a larger value of $z_{0\text{opt}}$.

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