Capacity Estimation of Optical Wireless Communication Systems over Moderate to Strong Turbulence Channels

Hector E. Nistazakis, George S. Tombras, Antreas D. Tsigopoulos, Evangelia A. Karagianni, and Michael E. Fafalios

Abstract: **Optical wireless communication (OWC) systems are rapidly gaining popularity as effective means of transferring data at high rates over short distances. OWC facilitates rapidly deployable, lightweight, high-capacity communication without licensing fees and tariffs. Nevertheless, the performance of this new technology depends strongly on the atmospheric conditions and the characteristics of the link. In this work, we study the influence of these parameters on both the average (ergodic) capacity and the outage capacity of an OWC system over moderate to strong turbulence channels modeled by gamma-gamma distribution. Moreover, we compare the results that we obtain estimating the average and outage capacities.**

Index Terms: **Channel capacity, gamma-gamma distribution, optical wireless communication (OWC) systems.**

I. INTRODUCTION

Optical wireless is a potentially high capacity and cost-effective communications technique that receives growing attention and commercial interest [1]–[3]. For an outdoor line-of-sight, point-to-point optical channel link, the atmospheric turbulence is a very important capacity mitigation factor since the received optical signal intensity fluctuates in a similar fashion as RF signals do experiencing fading. Therefore, it is reasonable to expect that in a real optical communication environment, optical channels will appear to have randomly time-varying characteristics due to the so called scintillation [4].

In the cases of fast fading channels, the fluctuations of the signal intensity are supposed to be so rapid that there is a different from the one symbol to another independently. In these cases the average (ergodic) capacity of the channel, represents the achievable capacity of a real free space optical link [5]–[11]. On the other hand, in the cases of quasi-static channels (i.e., slow fading channels), the performance of such links can be described by the outage capacity [12], [13].

In this work, we present the mathematical formulation for both, average and outage capacities for the cases of fast and slow fading channels respectively. We derive a closed-form expression for the average (ergodic) capacity of a wireless optical link over atmospheric turbulence-induced fast fading channels as modeled by gamma-gamma distribution. Finally, we present results that indicate the influence of various parameters on both, the average and the outage capacity of a practical wireless optical link.

The remaining of the paper is organized as follows. In Sections II and III we discuss on the estimation of the average and the outage capacity of fast and slow variant channels respectively. In Section IV we present the considered gamma-gamma wireless optical channel model and we derive a closed-form expression for its achievable average capacity. In the same section we present the mathematical expression for the estimation of the outage capacity for the above-mentioned signal intensity distribution model. Finally, the obtained results are presented and discussed in Section V. Concluding remarks are outlined in Section VI.

II. AVERAGE CAPACITY ESTIMATION

We consider an OWC system using intensity modulation/direct detection (IM/DD). The laser beams propagate along an horizontal path through a turbulence channel with additive white Gaussian noise (AWGN). The channel is assumed memoryless, stationary and ergodic, with independent and identically distributed (i.i.d.) intensity fast fading statistics. In this case, the statistical channel model is given by [5], [14]:

$$y = sx + n = \eta I x + n \tag{1}$$

where y is the signal at the receiver, $s = \eta I$ is the instantaneous intensity gain, η is the effective photo-current conversion ratio of the receiver, I is the normalized irradiance, x is the modulated signal (and takes values 0 or 1), and n is the AWGN with zero mean and variance $N_0/2$.

A real wireless channel is a randomly variant channel so the received instantaneous electrical signal-to-noise ratio (SNR) is also a random variable $\gamma = s^2/N_0$ [5], [14]. In this case, the channel capacity must be considered as a random variable [7], [8], and its average value, is known as average or ergodic capacity, $< C >$. As mentioned above the limitation for the validity of the average (ergodic) capacity, is the fast fading statistics of the channel, i.e. changes from one symbol to another independently. In these cases, the average capacity will indicate the average (practical) best rate for error-free transmission. Representing the probability density function (pdf) of γ as $p_\gamma(\gamma)$, the average channel capacity will be:

$$< C > = \int_0^{+\infty} B \log_2(1+\gamma) p_\gamma(\gamma) d\gamma. \tag{2}$$

From (2), we can estimate the average achievable capacity of a wireless optical channel due to signal intensity fluctuations

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caused by atmospheric turbulence. If γ is the received instantaneous electrical SNR, it is well accepted that for moderate to strong atmospheric turbulence-induced fading channels the gamma-gamma distribution is the most suitable [3], [4], [8]–[10]. This choice arises from the fact that this model can be directly related to atmospheric parameters and, thus, can be considered valid even up to strong turbulence.

III. OUTAGE CAPACITY ESTIMATION

In the cases where the above-mentioned OWC system is quasi static (i.e., the intensity of the optical signal follows slow fading statistics) the ergodic capacity is not an accurate magnitude for the evaluation of its performance. Thus, we evaluate the outage capacity, C_{out}, which is the capacity guaranteed for a percentage rate of $(100 - r\,[\%])$ of the channel realizations [12]:

$$Pr\left[C < C_{out}\right] = r\,[\%]. \tag{3}$$

Taking into account that in a real wireless channel the instantaneous electrical SNR at the receiver, γ, is a — slow varying in this case — random variable we conclude that the instantaneous channel capacity is a random variable too. Thus, if the pdf of the instantaneous capacity C, is represented as $p_C(C)$, the above probability (3) can be evaluated as:

$$r\,[\%] = 100\int_0^{C_{out}} p_C(C)dC. \tag{4}$$

From (4), it is feasible to estimate the outage capacity of an OWC link due to slow varying signal intensity at the receiver caused by the atmospheric turbulence conditions. As mentioned above, for moderate to strong atmospheric turbulence-induced fading channels the gamma-gamma distribution is the most suitable.

IV. THE GAMMA-GAMMA OPTICAL WIRELESS CHANNEL MODEL

The pdf of the gamma-gamma distributed signal irradiance I, has the following form [11],

$$p_I(I) = \frac{2(ab)^{\frac{a+b}{2}}}{\Gamma(a)\Gamma(b)} I^{\frac{a+b}{2}-1} K_{a-b}\left(2\sqrt{abI}\right) \tag{5}$$

where $K_\nu(\cdot)$ is the modified Bessel function of the second kind of order ν, and $\Gamma(\cdot)$ is the gamma function, [3], [11], [15]. The parameters a, b can be directly related to atmospheric conditions through the following expressions,

$$a = \left[\exp\left(\frac{0.49\delta^2}{\left(1 + 0.18d^2 + 0.56\delta^{12/5}\right)^{7/6}}\right) - 1\right]^{-1} \tag{6}$$

and

$$b = \left[\exp\left(\frac{0.51\delta^2}{\left(1 + 0.9d^2 + 0.62d^2\delta^{12/5}\right)^{5/6}}\right) - 1\right]^{-1} \tag{7}$$

while $d = kD^2/4L$, $k = 2\pi/\lambda$ is the optical wave number, λ is the wavelength, L is the length of the link, and D is the aperture diameter of the receiver. The parameter δ^2 is the Rytov variance and in this case, is given by $\delta^2 = 0.5C_n^2k^{7/6}L^{11/6}$, where C_n^2 is the turbulence strength, which is altitude dependent and varies from $10^{-17}\mathrm{m}^{-2/3}$ to $10^{-13}\mathrm{m}^{-2/3}$ for weak up to strong turbulence conditions, respectively.

From (5), we obtain the following pdf for the instantaneous electrical SNR, γ, at the receiver,

$$p_\gamma(\gamma) = \frac{(ab)^{\frac{a+b}{2}}}{\Gamma(a)\Gamma(b)} \frac{\gamma^{\frac{a+b}{4}-1}}{\Gamma^{\frac{a+b}{4}}} K_{a-b}\left(2\sqrt{ab\sqrt{\frac{\gamma}{\Gamma}}}\right) \tag{8}$$

where Γ is the average electrical SNR at the receiver, given by $\Gamma = (\eta E[I])^2/N_0$, and $E[\cdot]$ is the expected value [5], [6].

In order to evaluate the average capacity of a fast fading optical channel modeled with the gamma-gamma distribution we substitute (8) into (2) and the following integral is obtained:

$$\begin{aligned} < C > = {} & \frac{B\left(ab/\sqrt{\Gamma}\right)^{\frac{a+b}{2}}}{\Gamma(a)\Gamma(b)\ln(2)} \\ & \times \int_0^{+\infty} \ln(1+\gamma)\gamma^{\frac{a+b}{4}-1} K_{a-b}\left(2\sqrt{ab\sqrt{\frac{\gamma}{\Gamma}}}\right) \end{aligned} \tag{9}$$

and by expressing $\ln(1+\gamma)$ and $K_\nu(\cdot)$ as in [15], a closed-form mathematical expression will be derived as shown in the mathematical expression that follows [9],

$$\begin{aligned} < C > = {} & \frac{B\left(ab/\sqrt{\Gamma}\right)^{\frac{a+b}{2}}}{4\pi\Gamma(a)\Gamma(b)\ln(2)} \\ & \times G_{2,6}^{6,1}\left(\frac{(ab)^2}{16\Gamma}\,\middle|\,\begin{matrix} -\frac{y_1}{4}, -\frac{y_1}{4}+1 \\ \frac{y_2}{4}, \frac{y_2+2}{4}, -\frac{y_2}{4}, \frac{-y_2+2}{4}, -\frac{y_1}{4}, -\frac{y_1}{4} \end{matrix}\right) \end{aligned} \tag{10}$$

where $y_1 = a + b$, $y_2 = a - b$, and $G_{p,q}^{m,n}[\cdot]$ is the Meijer G-function, [15], which is a standard built-in function in most of the well-known mathematical software packages. Additionally, using [16], this function can be written in terms of the more familiar generalized hypergeometric functions. It is significant to mention here that in the case where $b = 1$, the gamma-gamma distribution [see (5)] becomes a K-distribution model which is valid for the cases of strong turbulence conditions [5], [6]. In this case the average channel capacity of the channel, which is given in [5], can be obtained from the above form (10), by substituting the parameter b with $b = 1$.

For the cases of slow fading optical channels modeled with the gamma-gamma distribution, the pdf of $\tilde{C} = C/B$ is evaluated from (8) and the well known equation for the capacity of an AWGN channel,

$$\tilde{C} = \frac{C}{B} = \log_2(1+\gamma) \tag{11}$$

and has the form,

$$\begin{aligned} p_{\tilde{C}}(\tilde{C}) = {} & \frac{2^{\tilde{C}}\ln(2)(ab)^{\frac{a+b}{2}}}{\Gamma(a)\Gamma(b)} \frac{\left(2^{\tilde{C}}-1\right)^{\frac{a+b}{4}-1}}{\Gamma^{\frac{a+b}{4}}} \\ & \times K_{a-b}\left(2\sqrt{ab\sqrt{\frac{2^{\tilde{C}-1}}{\Gamma}}}\right) \end{aligned} \tag{12}$$

From (4) and (12), by expressing $K_\nu(\cdot)$ as Meijer's G-function and integrating [15], we obtain the following closed mathematical form for the evaluation of the outage capacity:

$$r[\%] = 100\int_0^{\tilde{C}_{out}} p_{\tilde{C}}(\tilde{C})d\tilde{C} = 100\frac{\left(ab/\sqrt{\Gamma}\right)^{\frac{a+b}{2}}}{\Gamma(a)\Gamma(b)} \times \tilde{C}_1^{\frac{a+b}{4}} G_{1,3}^{2,1}\left(ab\sqrt{\frac{\tilde{C}_1}{\Gamma}}\,\middle|\,\begin{matrix}1-\frac{y_1}{2}\\ \frac{y_2}{2}, -\frac{y_2}{2}, -\frac{y_1}{2}\end{matrix}\right) \quad (13)$$

where $\tilde{C}_1 = \left(2^{\tilde{C}_{out}} - 1\right)$, $\tilde{C}_{out} = C_{out}/B$, while the parameters $\tilde{C}$, y_1, y_2, a, b, are defined above. From (13), it is feasible to evaluate the outage capacity for every value of the parameter r.

V. NUMERICAL RESULTS

Using (10) we estimate the average capacity of fast fading optical wireless links. On the other hand, for the cases of slow fading channels we can use (13) to obtain their outage capacity. By knowing these results, we can derive useful conclusions for the performance of common optical wireless communication systems.

In this work, we concentrate on the most typical parameters of an OWC system. Hence, we estimate the average and the outage channel capacity, for slow and fast fading channels respectively, versus the average electrical SNR at the receiver, Γ, for two values of the turbulence strength, C_n^2, two values for the length of the optical link, L, and two values for aperture diameter of the receiver, D. For the estimation of the outage capacity we set the parameter r to the value 10% which is a common value for the slow fading communication systems [12]. Below we present all these cases considering that an operation wavelength has been equal to $\lambda = 1.55\mu$m which is the wavelength that the most OWC systems are using [2]. It is obvious that using (10) and (13) it is possible to evaluate the average and the outage capacities for any other value of the above-mentioned parameters of the optical link.

More specifically, Fig. 1 presents the average and outage capacities for $r = 10\%$, of a wireless optical channel versus Γ, for two values of the C_n^2 (i.e., moderate and strong turbulence conditions) and $L = 1000$m, $D = 0.05$m. We observe that the average capacity, $< C > /B$, in the case of moderate ($C_n^2 = 1.0 \times 10^{-14}\text{m}^{-2/3}$) turbulence strength is larger than in the case of strong ($C_n^2 = 5.0 \times 10^{-14}\text{m}^{-2/3}$) for every value of Γ. For example, for $\Gamma = 30$ dB the average capacity which corresponds to the moderate C_n^2 is larger by a rate of 2.02% from the average capacity that corresponds to the strong turbulence. Similar qualitative results are obtained for the outage capacity. Thus, for every value of Γ the outage capacity that corresponds to the moderate turbulence is larger. Particularly, for $\Gamma = 30$ dB as above, the equivalent discrepancy between the two values of the outage capacity is 11.14%. It is obvious, that the outage capacity is affected stronger than the average capacity from the atmospheric turbulence conditions. This conclusion is clearer for longer link lengths where the influence of the atmospheric turbulence is getting stronger. Thus, in Fig. 2, we present the average capacity and the outage capacity with $r = 10\%$, for the same value of D as in Fig. 1, i.e. $D = 0.05$m, but for $L = 4000$m. In this case, it is clear that the values of average and outage capacities that correspond to the moderate turbulence strength are fairly larger than the ones that correspond to the strong, comparing them with the case presented in Fig 1. Thus for $\Gamma = 30$ dB, the average capacity corresponds to the large value of C_n^2 is smaller than the other one by a rate of 22.19%, while the equivalent rate for the outage capacity is 73.53%.

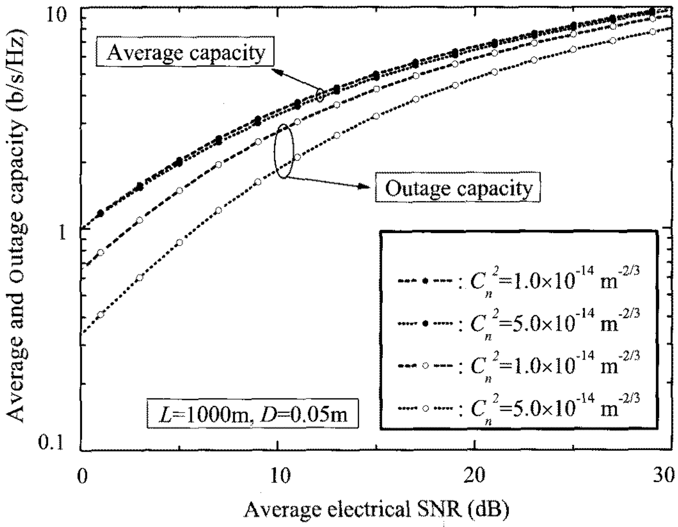

Fig. 1. Normalized average, $< C > /B$, and outage capacity C_{out}/B for $r = 10\%$, of a — fast and slow fading respectively — wireless optical channel versus the average electrical SNR, Γ, for moderate ($C_n^2 = 1.0 \times 10^{-14}\text{m}^{-2/3}$) and strong ($C_n^2 = 5.0 \times 10^{-14}\text{m}^{-2/3}$) turbulence conditions, with $L = 1000$m, $D = 0.05$m.

Another significant parameter for the performance of an OWC system is the aperture diameter of the receiver, D. In Fig. 3 we evaluate the average capacity of an optical wireless channel with the same link length as in Fig. 1, i.e., $L = 1000$m, but with $D = 0.01$m. From Figs. 1 and 3 we conclude that for the moderate turbulence case ($C_n^2 = 1.0 \times 10^{-14}\text{m}^{-2/3}$), the decrease of D from 0.05m to 0.01m, reduces slightly both the average capacity and the outage capacity (for $r = 10\%$), for every value of Γ. Thus, for $\Gamma = 30$ dB the former reduces 0.86% while the latter 1.34%. On the other hand, for strong turbulence conditions ($C_n^2 = 5.0 \times 10^{-14}\text{m}^{-2/3}$), the same variation of D, leads to a significant decrease of the average and outage capacity of 6.89% and 13.76%, respectively.

In Fig. 4, we present the average and the outage capacities for the large link length and the small aperture diameter of the receiver, i.e. $L = 4000$m and $D = 0.01$m. From Figs. 2 and 4, it is easy to conclude that the decrease of D induces a very large reduce of both capacities even for moderate turbulence conditions ($C_n^2 = 1.0 \times 10^{-14}\text{m}^{-2/3}$). In this case, for $\Gamma = 30$dB the average capacity reduces at a rate of 10.81% while the outage, for the same r as above, with a rate of 30.34%. The tremendous decrease of the capacities with the decrease of D, is obvious for the case of strong turbulence ($C_n^2 = 5.0 \times 10^{-14}\text{m}^{-2/3}$). Thus, for the same value of Γ as above the equivalent rates are 61.78%

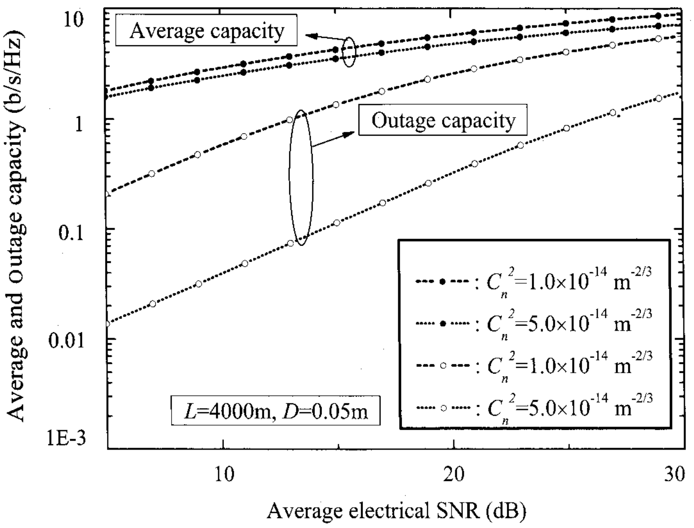

Fig. 2. Normalized average, $< C > /B$, and outage capacity C_{out}/B for $r = 10\%$, of a — fast and slow fading respectively — wireless optical channel versus the average electrical SNR, Γ, for moderate ($C_n^2 = 1.0 \times 10^{-14}\text{m}^{-2/3}$) and strong ($C_n^2 = 5.0 \times 10^{-14}\text{m}^{-2/3}$) turbulence conditions, with $L = 4000$m, $D = 0.05$m.

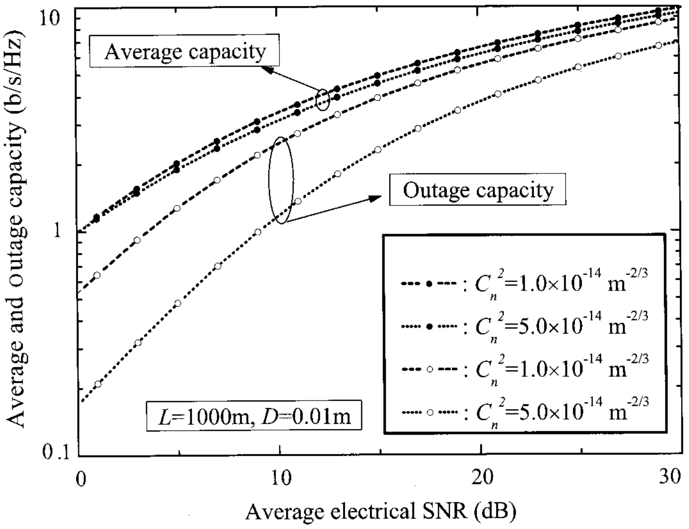

Fig. 3. Normalized average, $< C > /B$, and outage capacity C_{out}/B for $r = 10\%$, of a — fast and slow fading respectively — wireless optical channel versus the average electrical SNR, Γ, for moderate ($C_n^2 = 1.0 \times 10^{-14}\text{m}^{-2/3}$) and strong ($C_n^2 = 5.0 \times 10^{-14}\text{m}^{-2/3}$) turbulence conditions, with $L = 1000$m, $D = 0.01$m.

and 99.63%. Moreover, by comparing Figs. 3 and 4, i.e., link lengths $L = 1000$m and 4000m with $D = 0.01$m, we conclude that increase of L, results a large reduction of both capacities of the optical wireless system. More specifically, for the case of moderate turbulence ($C_n^2 = 1.0 \times 10^{-14}\text{m}^{-2/3}$) the increasing of L, from 1000m to 4000m, decreases the average and the outage capacity of 19.01% and 55.58%, respectively, while for strong turbulence conditions ($C_n^2 = 5.0 \times 10^{-14}\text{m}^{-2/3}$) this decrease is 69.81% and 99.91%, respectively. From the above results it is clear that both capacities achieve very small values, even for large values of the average electrical SNR at the receiver, when the length of the link is long and the aperture diameter of the receiver is small.

The above results show that the atmospheric turbulence conditions affect the outage and the average capacities, and thus the performance, of an OWC. This influence is very strong in the cases of long optical links and small aperture diameters of the receiver. Hence, taking into account these results, we conclude that a long length OWC system, in a strong atmospheric turbulence environment can work properly only if the aperture diameter of the receiver is large enough.

As it mentioned above, the average capacity is an important metric for the evaluation of the performance of an OWC system with fast fading statistics. On the other hand, the outage capacity is useful for the cases of slow fading. Sometimes, in common optical wireless links is not easy to distinguish if a system follows slow or fast fading statistics. In these cases, the above close mathematical form expressions (10) and (13), as well as the above-mentioned results, can help to estimate the minimum (i.e. the outage capacity) and the maximum (i.e., the average capacity) performance of the system with the specific parameters of the optical link.

Finally, it is worthy to mention here that using one of the well-known mathematical software packages, we evaluated both capacities firstly by estimating the integrals (4) and (9) and secondly, using the closed mathematical form expressions (10) and (13) for the most of the presented cases. We found that the estimation error in all cases was smaller than $10^{-6}\%$. Consequently, we conclude that the equations (10) and (13) are accurate mathematical form expressions for the estimation of the average and outage capacity, respectively.

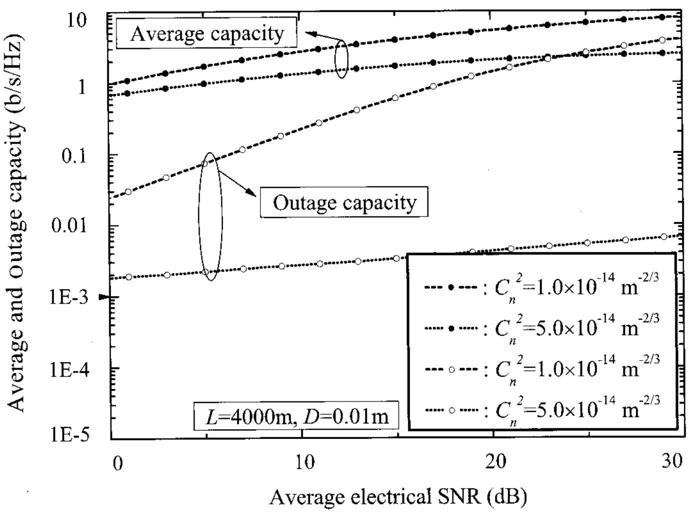

Fig. 4. Normalized average, $< C > /B$, and outage capacity C_{out}/B for $r = 10\%$, of a — fast and slow fading respectively — wireless optical channel versus the average electrical SNR, Γ, for moderate ($C_n^2 = 1.0 \times 10^{-14}\text{m}^{-2/3}$) and strong ($C_n^2 = 5.0 \times 10^{-14}\text{m}^{-2/3}$) turbulence conditions, with $L = 4000$m, $D = 0.01$m.

VI. CONCLUSIONS

In this work, we have estimated and derived closed-form expressions for the average and the outage capacity of a real OWC system using the gamma-gamma distribution model to describe the — fast and slow, respectively — fluctuations of the signal during its propagation. Moreover, we have indicated the parameters that play an important role in the performance of the optical link. We investigated their influence and we presented results suggesting the cases that increase the achievable link efficiency.

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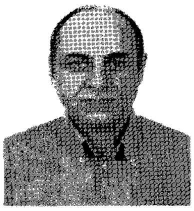

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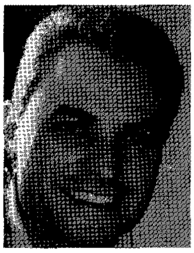

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