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On the use of wavelength and time diversity in optical wireless communication systems over gamma–gamma turbulence channels

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ABSTRACT

Optical wireless communication or free space optical systems have gained significant research and commercial attention in recent years due to their cost-effective and license-free high bandwidth access characteristics. However, by using the atmosphere as transmission media, the performance of such a system depends on the atmospheric conditions that exist between transmitter and receiver. Indeed, for an outdoor optical channel link, the existence of atmospheric turbulence may significantly degrade the performance of the associated communication system over distances longer than 1 or even 0.5 km. In order to anticipate this, particular attention has been given to diversity methods. In this work, we consider the use of wavelength and time diversity in wireless optical communication systems that operate under weak to strong atmospheric turbulence conditions modeled by the gamma–gamma distribution, and we derive closed form mathematical expressions for estimating the system's achievable outage probability and average bit error rate. Finally, numerical results referred to common practical cases are also obtained in order to show that wavelength and time diversity schemes enhances considerably these systems' availability and performance.

1. Introduction

It is recognized that there is an increasing research and commercial interest for optical wireless communication – or free space optical (FSO) – systems, since they combine license free high bandwidth access and security at low installation and operation cost, [1–4]. As it is for every communication link, the operation characteristics of an FSO link greatly depend on the (optical) channel state, i.e., on the atmospheric conditions in the area between the transmitter and the receiver. In this respect, one of the significant reliability and performance mitigation factors is the atmospheric turbulence, [2,5–8], which, for a typical outdoor line-of-sight, point-to-point optical link, may cause even rapid fluctuations of the propagated signal at the receiver input. It is, therefore, reasonable to expect that outdoor optical channels will appear to have randomly time-varying characteristics due to the so-called scintillation caused by turbulence, [9–13], and in conclusion, it is clear that this turbulence, affecting the optical channel characteristics, degrades the overall FSO systems' performance and reliability.

In order to combat the atmospheric turbulence deterioration effect on the operation of FSO links, particular attention has been given to diversity methods, which being popular in wireless radio, can be used in optical wireless, as well. In principle, the use of diversity refers to the consideration of multiple copies of the propagated signals in an attempt to overcome a poor transmission media state and enhance the communications systems' reliability and performance.

Diversity can generally be realized in space, in time or in wavelength, [7,14–18]. Using spatial diversity, [14,15], an FSO system incorporates multiple transmitters and receivers at different places that send and receive copies of the same signal, resulting to a decreased probability of error, [7]. In time diversity schemes, [16], the system uses a single transmitter—receiver pair, but the signal is retransmitted at different time slots and the total effective bit rate of the link is decreasing. Finally, when wavelength diversity is employed, [7,17,18], FSO systems use a composite transmitter and the signal is transmitted at the same time at different wavelengths towards a number of receivers [19], each of which detects the signal at a specific only wavelength.

In this work, we consider the use of wavelength and time diversity in FSO systems that operate under weak to strong atmospheric turbulence as modeled by the gamma–gamma

Abbreviations: AWGN, Additive White Gaussian Noise FSO: Free Space Optical; BER, Bit Error Rate; CSI, Channel State Information; cdf, cumulative distribution function; iid, independent and identically distributed; IM/DD, Intensity Modulation/Direct Detection; OC, Optimal Combining; OOK, On–Off Keying; pdf, probability density function; SIMO, Single Input Multiple Output; SNR, Signal to Noise Ratio

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distribution model, [10,20–22] and evaluate their reliability and performance by estimating the achieved outage probability, average bit error rate (BER), and maximum effective bit rate (only for the time diversity scheme), respectively. In this respect, we derive closed-form expressions for estimating these metrics for both, a wavelength and a time diversity scheme as emulated by optimal-combining (OC) method at the receiver-end, [14,15], and we present numerical results for common operational cases and atmospheric turbulence conditions.

The remainder of the paper is organized as follows: in Section 2, we introduce the considered FSO system and channel model for both wavelength and time diversity schemes. In Section 3, we derive closed-form mathematical expressions for the estimation of the outage probability of the wavelength and time diversity FSO systems, in Section 4, we present the expressions for the average BER, while in Section 5, we show the corresponding mathematical forms for the maximum effective bit rate. In Section 6, we present numerical results for the systems' reliability and performance for various links' parameters. Final conclusions are presented in Section 7.

2. The FSO system with time or wavelength diversity

The incorporation of wavelength diversity in an FSO system can be modeled as a communication system that uses a composite transmitter, transmitting a signal at different operational wavelengths at the same time towards a set of receivers, each of which detects the signal at a specific only wavelength. This can be further explained as following.

Suppose that an FSO system consists of M different trans-receivers and the signal is transmitted simultaneously by the M transmitters at M different wavelengths. Then, each m-th of these copies of the signal, $m=1,\ldots,M$, will be detected only by the m-th receiver provided that it "recognizes" only the m-th wavelength. Indeed, taking into account that optical receivers operate properly only in a relatively narrow region around their nominal operational wavelength, the m-th signal in the m-th receiver will originate only from the m-th transmitter that transmits at the m-th wavelength. Hence, since each transmitter transmits only at a specific wavelength and, therefore, towards a specific only receiver, the wavelength diversity scheme for an FSO link can be seen to consist of a composite transmitter transmitting along M wavelength branches to the M receivers, [7]. Moreover, it is worth mentioning here that for link distances of the order of a few kilometers, if the aperture separation of the photodetectors is of order of centimeters, these M receivers will be practically uncorrelated, [23,24].

Following the above, we now consider the m-th laser beam as it propagates along a horizontal path through a turbulence channel with additive white Gaussian noise (AWGN). The channel is assumed to be memoryless, stationary and ergodic, with independent and identically distributed (i.i.d.) intensity fast fading statistics, with binary input and continuous output, intensity modulation/direct detection (IM/DD) with On–Off Keying (OOK) modulation, while the channel state information (CSI) is available at both transmitter and receiver. In this case, the statistical channel model can be expressed as in [15,20,25]:

$$y_m = s_m x + n = \eta_m x I_m + n, \quad m = 1,\ldots,M \tag{1}$$

where y_m is the output signal of each of the M receivers, $s_m=\eta_m I_m$ is the instantaneous intensity gain, η_m is the effective photo-current conversion ratio of each receiver, I_m is the normalized irradiance arrived in each receiver, x is the modulated signal (taking the binary values "0" or "1"), and n represents the additive white Gaussian noise (AWGN) with zero mean and variance equal to $N_0/2$, [20,26].

Following a similar approach, the use of time diversity scheme in an FSO system can be modeled as a communication system that uses one transmitter that transmits M copies of the signal at M different time-slots and one receiver system that uses the OC reception technique for these M copies. Clearly, such an operation is equivalent to the combined operation of one transmitter transmitting through M channel/branches and M receivers at the receiving end, similar with the case of the wavelength diversity. Thus, the corresponding statistical channel model for a laser beam propagating along a horizontal path with the same characteristics mentioned in the case of wavelength diversity can be seen to consist of M branches, and it will have the same form as Eq. (1) assuming that the effective photo-current conversion ratio (i.e., η) is unique since a single receiver is used.

For weak to strong atmospheric turbulence conditions, the turbulence induced fading can be assumed as a random process that follows the gamma–gamma distribution, [10,20,21,27,28]. The probability density function (pdf) of the gamma–gamma distribution is given by, [10]:

$$f_{I_m}(I_m) = \frac{2(a_m b_m)^{a_m+b_m/2}}{\Gamma(a_m)\Gamma(b_m)} I_m^{\frac{a_m+b_m}{2}-1} K_{a_m-b_m}\left(2\sqrt{a_m b_m I_m}\right) \tag{2}$$

where $K_v(.)$ is the modified Bessel function of the second kind of order v, $\Gamma(.)$ is the gamma function. In addition, a_m and b_m can be directly related to link's parameters, through the expressions, [21,29]:

$$a_m = \left[\exp\left(\frac{0.49\delta_m^2}{(1+0.18d_m^2+0.56\delta_m^{12/5})^{7/6}}\right)-1\right]^{-1}$$
$$b_m = \left[\exp\left(\frac{0.51\delta_m^2(1+0.69\delta_m^{12/5})^{-5/6}}{(1+0.9d_m^2+0.62d_m^2\delta_m^{12/5})^{5/6}}\right)-1\right]^{-1} \tag{3}$$

where $d_m = \sqrt{k_m D^2/4L}$, $k_m=2\pi/\lambda_m$, is the optical wave number, with λ_m being the operational wavelength of each of the M channels of the FSO system with wavelength diversity, L is the length of the optical link and D is the receiver's aperture diameter [20]. The parameter δ_m^2 is the Rytov variance and is given as $\delta_m^2 = 0.5C_n^2 k_m^{7/6} L^{11/6}$, for spherical wave propagation in a horizontal path [20,21,29]. The Rytov variance, or scintillation strength, is a parameter which measures the severity of intensity scintillation caused by the distributed atmospheric turbulence [30]. The C_n^2 represents the refractive index structure parameter, depends on the altitude and the atmospheric conditions and is given as $C_n^2=(79\times 10^{-6}P/T^2)^2 C_T^2$, where P, T and C_T^2, stands for the atmospheric pressure, the temperature and the temperature structure constant, respectively [31]. In practice, several profile models for the C_n^2 have been proposed, but the most commonly used model is the Hufnagle-Valley which is given as:

$$C_n^2(h) = 0.00594\left(\frac{w}{27}\right)^2(10^{-5}h)^{10}\exp\left(\frac{h}{1000}\right)+2.7 \times 10^{-6}\exp\left(-\frac{h}{1500}\right)+C_n^2(0)\exp\left(-\frac{h}{1000}\right) \tag{4}$$

where h is the altitude in meters, w is the wind speed in meters per second and $C_n^2(0)$ is the value of $C_n^2(h)$ at the ground in $m^{-2/3}$ [5,29,31–33]. A typical value for $C_n^2(0)$ is 1.7×10^{-14} $m^{-2/3}$, [5,32]. In general, C_n^2 varies from 10^{-17} $m^{-2/3}$ to 10^{-13} $m^{-2/3}$ for weak to strong turbulence conditions, respectively. It is worth mentioning here, that although the strength of the optical turbulence is typically expressed by the so-called atmospheric coherence diameter of the Fried parameter r_0, [32,34], roughly, the C_n^2 parameter can be used as a metric of the atmospheric turbulence strength, because of their mutual dependence [32].