Outage Performance of DF Relay-Assisted FSO Communications Using Time Diversity

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***Abstract*— Outage probability as a performance measure for a decode-and-forward (DF) relaying scheme based on repetition coding with the relay is presented in the context of free-space optical (FSO) communication systems with intensity modulation and direct detection over atmospheric turbulence and misalignment fading channels. Novel closed-form asymptotic expressions for the outage probability are derived for a three-way FSO communication setup when the irradiance of the transmitted optical beam is susceptible to moderate-to-strong turbulence conditions, following a gamma–gamma distribution, and pointing error effects, following a misalignment fading model where the effect of beam width, detector size, and jitter variance is considered. Fully exploiting the potential time-diversity available in the relay turbulent channel, a greater robustness to the relay location and pointing errors is achieved, maintaining a high diversity gain regardless of the source-destination link distance and remarkably superior to that of the two-transmitter case as well as the conventional DF scheme. Simulation results are further demonstrated to confirm the accuracy and usefulness of the derived results.**

***Index Terms*— Outage probability, decode-and-forward (DF) relaying, free space optical (FSO) links, Gamma-Gamma fading, time diversity.**

I. Introduction

ATMOSPHERIC free-space optical (FSO) transmission using intensity modulation and direct detection (IM/DD) can be considered as an important alternative to consider for next generation broadband, providing large bandwidth, excellent security, and quick setup [1]. However, this technology is not without drawbacks, being the atmospheric turbulence one of the most impairments, producing fluctuations in the irradiance of the transmitted optical beam, which is known as *atmospheric scintillation*, severely degrading the link performance [2]. Since FSO systems are usually installed on high buildings, building sway causes vibrations in the transmitted beam, leading to an unsuitable alignment between transmitter and receiver and, hence, a greater deterioration in performance. Cooperative transmission can significantly improve the performance by creating diversity using the transceivers available at the other nodes of the network [3]–[7]. In [6] outage performance is investigated for the multi-hop parallel relaying scheme assuming log-normal atmospheric turbulence.

Manuscript received April 29, 2014; revised February 11, 2015; accepted March 3, 2015. Date of publication March 5, 2015; date of current version May 8, 2015. This work was supported by the Spanish Ministry of Economy and Competitiveness under Project TEC2012-32606.

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Digital Object Identifier 10.1109/LPT.2015.2410426

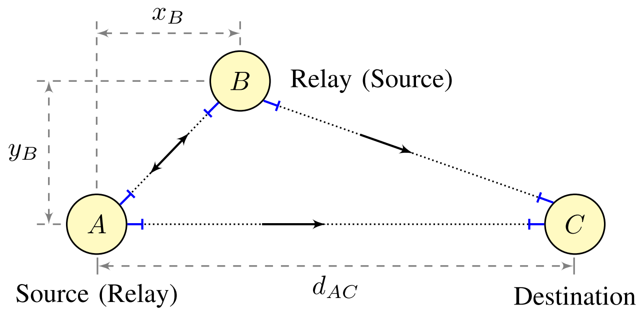


Fig. 1. Block diagram of the considered 3-way FSO communication system.

The motivation and purpose of this letter is the analysis of the outage probability as a performance measure for a decode-and-forward (DF) cooperative protocol using time diversity [7], based on repetition coding with the relay in the context of IM/DD FSO communication systems over atmospheric turbulence and misalignment fading channels. Novel closed-form asymptotic expressions for the outage probability are derived for a 3-way FSO communication setup when the irradiance of the transmitted optical beam is susceptible to moderate-to-strong turbulence conditions, following a gamma-gamma (GG) distribution, and pointing error effects, following a misalignment fading model where the effect of beam width, detector size and jitter variance is considered. To the best knowledge of the authors, the impact of pointing errors has not been considered in the outage performance analysis in the context of DF relay-assisted FSO communications using time diversity. Fully exploiting the potential time-diversity available in the relay turbulent channel, a greater robustness to the relay location and pointing errors is corroborated compared to other reported works as in [6], even when one relay is only assumed, maintaining a high diversity gain regardless of the source-destination link distance and remarkably superior to that of the two-transmitter case as well as the conventional decode-and-forward scheme. In this sense, we have corroborated that the diversity order gain depends not only on the number of relays but also on the relay location.

II. System and Channel Model

We adopt a three-node cooperative system as presented in [7], based on three separate full-duplex FSO links, as shown in Fig. 1. The cooperative strategy works in three phases or transmission frames. In the first phase, the nodes A and B send their own data to each other and the destination node C, i.e., the node A (B) transmits the same information to the nodes B (A) and C. In the second transmission frame, the nodes A and B send again the same information to each other delayed at least by the expected fade duration τ_c and, hence, assuming that channel fades are independent and identically distributed (i.i.d.) according to the frozen-atmosphere characteristics of optical turbulence. A minimum required buffer size corresponding to $R_b\tau$ symbols must be assumed, being $\tau > \tau_c$ and R_b the signaling rate. In the third phase, the node B (or A) sends the received data from its partner A (or B) in previous frames to the node C. Following the bit-detect-and-forward (BDF) cooperative protocol, the relay node (A or B) detects each code bit to "0" or "1" based on repetion coding and sends the bit with the new power to the destination node C. When repetition coding is used in the source-relay link transmission during the first and second phases, the information is detected each transmission frame, combining with the same weight two noisy faded signals as in equal gain combining (EGC) [5], [7]. It is here assumed that all the bits detected at the relay are always resended regardless of these bits are detected correctly or incorrectly. For each link in this three-node cooperative FSO system, the instantaneous current $y_m(t)$ in the receiving photodetector corresponding to the information signal transmitted from the laser is given by $y_m(t) = \eta i_m(t)x(t) + z_m(t)$ where η is the detector responsivity, assumed hereinafter to be the unity, $X \triangleq x(t)$ represents the optical power supplied by the source and $I_m \triangleq i_m(t)$ the equivalent real-valued fading gain (irradiance) through the optical channel between the laser and the receive aperture. $Z_m \triangleq z_m(t)$ is assumed to include any front-end receiver thermal noise as well as shot noise caused by ambient light much stronger than the desired signal at the detector, and modeled as AWGN with zero mean and variance $\sigma^2 = N_0/2$, i.e. $Z_m \sim N(0, N_0/2)$, independent of the on/off state of the received bit. We use Y_m, X, I_m and Z_m to denote random variables and $y_m(t)$, $x(t)$, $i_m(t)$ and $z_m(t)$ their corresponding realizations. The irradiance is considered to be a product of two independent random variables with the deterministic propagation loss L_m, i.e. $I_m = L_m I_m^{(a)} I_m^{(p)}$, representing $I_m^{(a)}$ and $I_m^{(p)}$ the attenuation due to atmospheric turbulence and the attenuation due to geometric spread and pointing errors, respectively. To consider a wide range of turbulence conditions, the GG turbulence model is here assumed [2]. Regarding to the impact of pointing errors, we use the general model of misalignment fading given in [8] by Farid and Hranilovic, wherein the effect of beam width, detector size and jitter variance is considered. The atmospheric loss L_m is determined by the exponential Beers-Lambert law as $L_m = e^{-\psi d}$, where d is the link distance and ψ is the attenuation coefficient. It is given by $\psi = (3.91/V(\text{km}))(\lambda(\text{nm})/550)^{-q}$ where V is the visibility in kilometers, λ is the wavelength in nanometers and q is a parameter related to the visibility, being $q = 1.3$ for average visibility (6 km $< V <$ 50 km) and $q = 0.16V + 0.34$ for haze visibility (1 km $< V <$ 6 km). A closed-form expression of the combined probability density function (PDF) of I_m was derived in [9] in terms of the Meijer's G-function [10, eq. (8.2.1)]. Here, an approximated expression is adopted in order to obtain simple closed-form expressions, assuming a single polynomial term as $f_{I_m}(i) \approx a_m i^{b_m - 1}$ since the asymptotic behavior of the system performance is dominated by the behavior of the PDF near the origin [11]. Different expressions for $f_{I_m}(i)$, depending on the relation between the jitter variance and turbulence conditions [5], can be written as

$$f_{I_m}(i) \approx a_m i^{b_m-1} = \begin{cases} \dfrac{\varphi^2(\alpha\beta)^\beta \Gamma(\alpha-\beta) i^{\beta-1}}{(A_0 L_m)^\beta \Gamma(\alpha)\Gamma(\beta)\left(\varphi^2-\beta\right)}, & \varphi^2 > \beta \\ \dfrac{\varphi^2 \Gamma\left(\alpha-\varphi^2\right)\Gamma\left(\beta-\varphi^2\right) i^{\varphi^2-1}}{(\alpha\beta)^{-\varphi^2}(A_0 L_m)^{\varphi^2}\Gamma(\alpha)\Gamma(\beta)}, & \varphi^2 < \beta \end{cases} \quad (1)$$

where $\Gamma(\cdot)$ is the well-known Gamma function, and α and β can be directly linked to physical parameters through the following expresions:

$$\alpha = \left[\exp\left(0.49\sigma_R^2/(1+1.11\sigma_R^{12/5})^{7/6}\right) - 1\right]^{-1} \quad (2a)$$

$$\beta = \left[\exp\left(0.51\sigma_R^2/(1+0.69\sigma_R^{12/5})^{5/6}\right) - 1\right]^{-1} \quad (2b)$$

being $\sigma_R^2 = 1.23 C_n^2 \kappa^{7/6} d^{11/6}$ the Rytov variance, which is a measure of optical turbulence strength. Here, $\kappa = 2\pi/\lambda$ is the optical wave number, λ is the wavelength and d is the link distance in meters. C_n^2 stands for the altitude-dependent index of the refractive structure parameter and varies from 10^{-13} m$^{-2/3}$ for strong turbulence to 10^{-17} m$^{-2/3}$ for weak turbulence [2]. Assuming a Gaussian spatial intensity profile of beam waist radius, ω_z, on the receiver plane at distance z from the transmitter and a circular receive aperture of radius r, $\varphi = \omega_{z_{eq}}/2\sigma_s$ is the ratio between the equivalent beam radius at the receiver and the pointing error displacement standard deviation (jitter) at the receiver, $\omega_{z_{eq}}^2 = \omega_z^2 \sqrt{\pi}\,\text{erf}(\upsilon)/2\upsilon \exp(-\upsilon^2)$, $\upsilon = \sqrt{\pi} r/\sqrt{2}\omega_z$, $A_0 = [\text{erf}(\upsilon)]^2$ and $\text{erf}(\cdot)$ is the error function. The beam waist ω_0 at the transmitting laser is approximately related to ω_z through $\omega_0 \approx \lambda z/\pi\omega_z$. Hereinafter, the fading coefficient I_m for the paths A-B, A-C and B-C is indicated by I_{AB}, I_{AC} and I_{BC}, respectively.

III. Outage Performance Analysis

In this section, outage performance related to the information transmission between the source node A and destination node C is analyzed wherein the node B is used as relay. A similar analysis can be applied to the symmetric scheme wherein the information transmission is established from node B to node C wherein the node A is working as relay. It must be noted that the three-node cooperative system here analyzed provides the simultaneous transmission of different information from nodes A and B, respectively, to node C, alternative to cooperative schemes wherein relays are mirror nodes. It is assumed that the average optical power transmitted from each node is P_{opt}, being adopted an on-off keying (OOK) signaling based on a constellation of two equiprobable points in a one-dimensional space with an Euclidean distance of $d_E = 2P_{\text{opt}}\sqrt{T_b \xi}$, where the parameter T_b is the bit period and ξ represents the square of the increment in Euclidean distance due to the use of a pulse shape of high peak-to-average optical power ratio (PAOPR) [5]. Outage probability, P_{out}, is defined as the probability that the instantaneous combined signal-to-noise ratio (SNR), γ_T, falls below a certain specified threshold, γ_{th}, which represents a protection value of the SNR above which the quality of the channel is satisfactory, i.e.,

$$P_{\text{out}} := P(\gamma_T \le \gamma_{th}) = \int_0^{\gamma_{th}} f_{\gamma_T}(i)\,di. \quad (3)$$

Firstly, the outage performance of the FSO system without relaying scheme is evaluated in order to be considered as a benchmark in the analysis of the BDF cooperative protocol using time-diversity. The statistical channel model corresponding to the direct path link can be written as

$$Y = X I_{AC} + Z_{AC}, \;\; X \in \{0, d_E\} \; Z_{AC} \sim N(0, N_0/2). \quad (4)$$

The received electrical SNR can be defined, as in [8], as

$$\gamma_{T_{\text{direct}}}(i) = \frac{1}{2}\frac{d_E^2}{N_0/2} i^2 = \gamma \xi i^2, \tag{5}$$

where $\gamma = 4P_{\text{opt}}^2 T_b/N_o$ represents the normalized received electrical SNR in absence of turbulence. Using Eq. (3), the outage probability can be written as

$$P_{\text{out}} = P(\gamma \xi i^2 \le \gamma_{th}) = \int_0^{\sqrt{\gamma_{th}/\gamma\xi}} f_{I_{AC}}(i) di. \tag{6}$$

With the expressions in Eq. (1), the asymptotic performance of the outage probability can easily obtained by

$$P_{\text{out}}^{\text{direct}} \doteq \left(\frac{a_{AC}^{2/b_{AC}}}{b_{AC}^{2/b_{AC}} L_{AC}^2 \xi} \frac{\gamma_{th}}{\gamma} \right)^{b_{AC}/2}. \tag{7}$$

It is straightforward to show that the outage probability behaves asymptotically as $(O_c\gamma)^{-O_d}$, where O_d and O_c denote outage diversity and coding gain, respectively [11]. From these results, it can be deduced that b_{AC} is a key parameter in order to optimize the outage diversity, not being dependent on the pointing errors when $\beta < \varphi^2$. Next, the outage performance of the BDF cooperative protocol using time diversity is analyzed, assuming an statistical channel model as follows

$$Y_{\text{BDF}} = \frac{1}{2} X I_{AC} + Z_{AC} + \frac{1}{2} X^* I_{BC} + Z_{BC}, \tag{8}$$

being $X \in \{0, d_E\}$, and $Z_{AC}, Z_{BC} \sim N(0, N_0/2)$, where X^* represents the random variable corresponding to the information detected at B and, hence, $X^* = X$ when the bit has been detected correctly at B and $X^* = d_E - X$ when the bit has been detected incorrectly. It must be here emphasized that node B is working as relay when analyzing the outage performance corresponding to the information tranmission from node A to node C. Knowing from [7] that the closed-form asymptotic solution for the bit error-rate (BER) corresponding to the A-B link can be written as

$$P_b^{AB} \doteq \frac{a_{AB}^2 2^{b_{AB}-1} \Gamma(b_{AB})}{b_{AB} L_{AB}^{2b_{AB}}} (\gamma \xi)^{-b_{AB}}, \tag{9}$$

the outage probability corresponding to the BDF cooperative protocol here analyzed is given by

$$P_{\text{out}}^{\text{BDF}} = P_{\text{out}}^0 \cdot (1 - P_b^{AB}) + P_{\text{out}}^1 \cdot P_b^{AB}. \tag{10}$$

where P_{out}^0 and P_{out}^1 are the outage performance when the bit is correctly and incorrectly detected at B, respectively. The resulting received electrical SNR in the first case, i.e. $X^* = X$, can be defined as $\gamma_{T_{BDF_0}} = \frac{\gamma\xi}{8}(i_{AC} + i_{BC})^2 = \frac{\gamma\xi}{8} i_T^2$, and, hence, the outage probability can be written as

$$P_{\text{out}}^0 = P\left(\frac{\gamma\xi}{8} i_T^2 \le \gamma_{th} \right) = \int_0^{\sqrt{8\gamma_{th}/\gamma\xi}} f_{I_T}(i) di. \tag{11}$$

Since the variates I_{AC} and I_{BC} are independent, knowing that the resulting PDF of their sum I_T can be determined by using the moment generating function of their corresponding PDFs, an approximate expression for the PDF, $f_{I_T}(i)$, of the combined variates can be easily derived as

$$f_{I_T}(i) \approx \frac{a_{AC} a_{BC} \Gamma(b_{AC}) \Gamma(b_{BC})}{L_{AC}^{b_{AC}} L_{BC}^{b_{BC}} \Gamma(b_{AC} + b_{BC})} i^{b_{AC}+b_{BC}-1}. \tag{12}$$

From this expression, the closed-form asymptotic solution for the outage performance is obtained as follows

$$P_{\text{out}}^0 \doteq \frac{a_{AC} a_{BC} 8^{\frac{b_{AC}+b_{BC}}{2}} \Gamma(b_{AC}) \Gamma(b_{BC})}{L_{AC}^{b_{AC}} L_{BC}^{b_{BC}} \Gamma(b_{AC} + b_{BC} + 1)} \left(\frac{\gamma_{th}}{\gamma} \right)^{\frac{b_{AC}+b_{BC}}{2}} \tag{13}$$

In relation to the second case, i.e. $X^* = d - X$, the resulting received electrical SNR can be defined as $\gamma_{T_{BDF_1}} = \frac{\gamma\xi}{8}(i_{AC} - i_{BC})^2$ and, hence, the outage probability can be written as

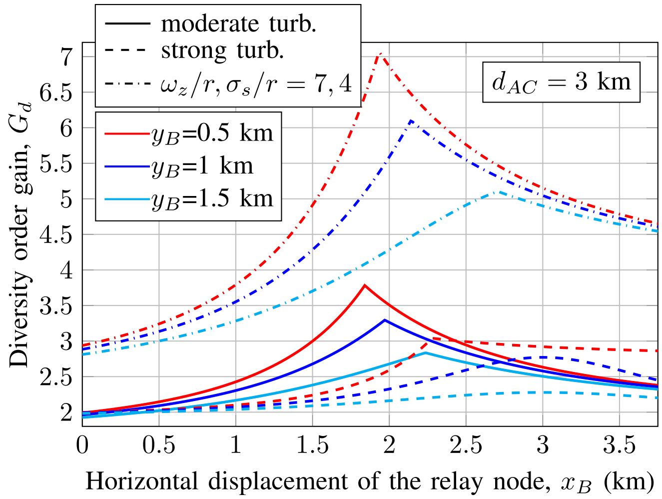
$$P_{\text{out}}^1 = P\left((i_{AC} - i_{BC})^2 \le \frac{8\gamma_{th}}{\gamma\xi} \right). \tag{14}$$

Due to the subtraction of the random variates, the approximate expression for the PDF cannot be here assumed. Taking into account the region of integration in Eq. (14), the limits of integration are changed as follows

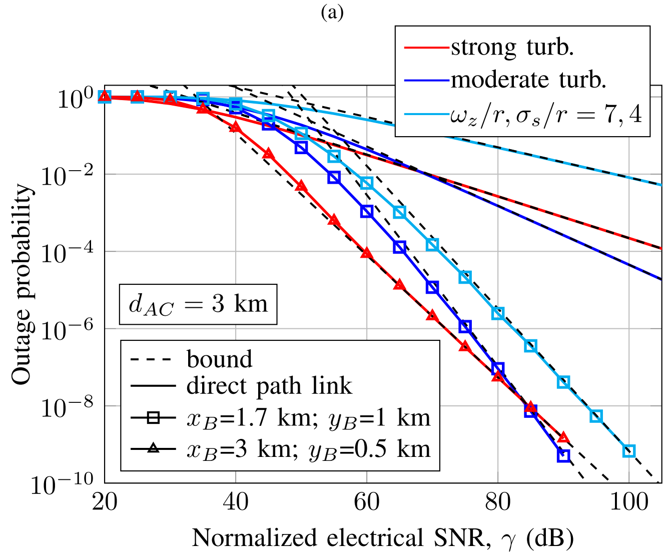
$$\begin{aligned} P_{\text{out}}^1 = & \int_0^{\infty} \int_0^{i_2 + \sqrt{8\gamma_{th}/\gamma\xi}} f_{I_{AC}}(i_1) f_{I_{BC}}(i_2) di_1 di_2 \\ & - \int_{\sqrt{8\gamma_{th}/\gamma\xi}}^{\infty} \int_0^{i_2 - \sqrt{8\gamma_{th}/\gamma\xi}} f_{I_{AC}}(i_1) f_{I_{BC}}(i_2) di_1 di_2. \end{aligned} \tag{15}$$

To evaluate these two-dimensional integrals, inner integrals are firstly reduced to a Meijer's G-function by using [10, eq. (2.24.2.2)]. Then, we can use [10, eq. (2.24.1.3)] to solve the unidimensional integrals involving the product of two Meijer's G-functions with shifted arguments, providing an analytical solution in terms of a summation of Meijer's G-function as can be seen in Eq. (16) at the bottom of the page. Knowing the fact that the value of this solution is negligible when $k = 0$, these expressions can be significantly simplified assuming that their corresponding asymptotic behavior is dominated by the term proportional to $\gamma^{-1/2}$, i.e. $k = 1$. Hence, it can be deduced from (10) that the adoption of the BDF cooperative

$$\begin{aligned} P_{\text{out}}^1 = & \frac{\sum_{k=0}^{\infty} \frac{1}{k!} \left(-\frac{\alpha_{AC}\beta_{AC}\sqrt{\frac{8\gamma_{th}}{\gamma\xi}}}{A_{AC}L_{AC}} \right)^k G_{6,6}^{4,4}\left(\frac{A_{AC}L_{AC}\alpha_{BC}\beta_{BC}}{A_{BC}L_{BC}\alpha_{AC}\beta_{AC}} \middle| \begin{matrix} 0, k-\alpha_{AC}, k-\beta_{AC}, k-\phi_{AC}^2, k, \phi_{BC}^2 \\ k-1, \alpha_{BC}-1, \beta_{BC}-1, \phi_{BC}^2-1, k, -\phi_{AC}^2+k-1 \end{matrix} \right)}{(A_{AC}L_{AC}\alpha_{BC}\beta_{BC}\phi_{AC}^2\phi_{BC}^2)^{-1} A_{BC}L_{BC}\Gamma(\alpha_{AC}+1)\Gamma(\alpha_{BC})\Gamma(\beta_{AC}+1)\Gamma(\beta_{BC})} \\ & -1 + \frac{\sum_{k=0}^{\infty} \frac{1}{k!} \left(-\frac{\alpha_{BC}\beta_{BC}\sqrt{\frac{8\gamma_{th}}{\gamma\xi}}}{A_{BC}L_{BC}} \right)^k G_{6,6}^{4,4}\left(\frac{A_{BC}L_{BC}\alpha_{AC}\beta_{AC}}{A_{AC}L_{AC}\alpha_{BC}\beta_{BC}} \middle| \begin{matrix} 0, k-\alpha_{BC}, k-\beta_{BC}, k-\phi_{BC}^2, k, \phi_{AC}^2 \\ k-1, \alpha_{AC}-1, \beta_{AC}-1, \phi_{AC}^2-1, k, -\phi_{AC}^2+k-1 \end{matrix} \right)}{(\alpha_{AC}A_{BC}\beta_{AC}L_{BC}\phi_{AC}^2\phi_{BC}^2)^{-1} A_{AC}\alpha_{BC}\beta_{BC}L_{AC}\Gamma(\alpha_{AC})\Gamma(\alpha_{BC})\Gamma(\beta_{AC})\Gamma(\beta_{BC})} \end{aligned} \tag{16}$$



(a)



(b)

Fig. 2. (a) Diversity order gain, G_d, and (b) Probability of outage versus normalized electrical SNR.

protocol using time diversity translates into a diversity order gain, G_d, relative to the non-cooperative link A-C of

$$G_d = \min(b_{AC} + b_{BC}, 1 + 2b_{AB})/(b_{AC}) \qquad (17)$$

IV. Numerical Results and Concluding Remarks

This diversity gain is despicted in Fig. 2a as a function of the horizontal displacement of the relay node, x_B, for $d_{AC} = 3$ km and different relay locations. Different weather conditions are considered: haze visibility of 4 km with $C_n^2 = 1.7 \times 10^{-14}$ m$^{-2/3}$ and average visibility of 16 km with $C_n^2 = 8 \times 10^{-14}$ m$^{-2/3}$, corresponding to moderate and strong turbulence, respectively. Together with $\lambda = 1550$ nm, α and β are calculated from Eq. (2). Pointing errors are here present assuming values of normalized beamwidth and jitter of $(\omega_z/r, \sigma_s/r) = (7, 1)$ for each link. A remarkable improvement in performance can be observed when comparing to the two-transmitter case as well as alternative cooperative protocols [3]–[6], presenting a diversity order gain superior to 2 or even greater than 3 for some relay locations. These conclusions are even better when the direct path link is subject to more severe pointing errors $(\omega_z/r, \sigma_s/r) = (7, 4)$, as shown in dash-dotted line. In this case, a moderate turbulence scenario has been adopted. The results corresponding to this asymptotic analysis with rectangular pulse shapes and $\xi = 1$ are illustrated in Fig. 2b (dashed line) for $\gamma_{th} = 0$ dB, corroborating an excellent agreement with previous Fig. 2a. To confirm the accuracy and usefulness of the derived bound, Monte Carlo simulation results taking into account the exact combined PDF are furthermore included by using Eq. (11) and Eq. (14). It can be seen that a diversity gain of nearly 3 is obtained when $(\omega_z/r, \sigma_s/r) = (7, 1)$ is assumed for each link. A relevant increase of the diversity gain to 4.7 is achieved when more severe pointing errors of $(\omega_z/r, \sigma_s/r) = (7, 4)$ are considered for the direct path link. It is concluded that not only a significant improvement in performance has been obtained but also that a greater robustness is now achieved regardless of the relay location and the presence of pointing errors.

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