# Performance of free-space optical communication systems using circle polarization shift keying with spatial diversity receivers

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A closed-form bit-error rate (BER) expression is derived for free-space optical (FSO) communication systems with circle polarization shift keying and spatial diversity receivers in the gamma-gamma (GG) distribution fading channel. This model can predict the performance without the need of lengthy simulation runs. The performance can be analyzed by some system parameters such as atmospheric conditions, link length, communication wavelength, receiver aperture size, and number of spatial diversity receivers. Numerical results demonstrate the influence of the above parameters on the FSO systems and show quantitatively the differences in behavior among various different parameters.

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Free-space optical (FSO) communication has several advantages over conventional radio frequency (RF) communication. It has attracted more significant attentions recently. However, when the FSO links are built up in the atmosphere, atmospheric turbulence will cause the fluctuations in both intensity and phase of the received light signal, which degrades the link performance[1]. Current FSO systems typically use intensity modulation with direct detection (IM/DD), such as on-off keying (OOK) modulation. Although OOK modulation is widely reported, it cannot perform optimally in that atmospheric-induced scintillation is a major impairment to cause random variations in signal intensity[2,3]. The threshold is required to be adjusted adaptively for OOK modulation in random communication environment. It makes the detection system more complicated. In atmospheric links, polarization state is well preserved over several kilometers[4]. Different from the intensity modulation, polarization shift keying (PolSK) uses the vector character of light wave and codes digital bits as different states of polarization (SOPs)[5]. PolSK modulation scheme has better sensitivity than OOK modulation. PolSK also has the simplicity in the system construction. It can be an attractive modulation scheme for FSO communication systems to improve the reliability and performance. For FSO communication, however, PolSK modulation scheme based on linear polarizations requires the alignment of polarization coordinates of transmitter and receiver. The requirement is not easy or even impossible to be satisfied for the FSO systems installed on moving objects. In order to avoid this requirement, circle polarization shift keying (CPolSK) modulation scheme, which implements the binary modulation based on the two rotation states of circle polarization, is considered for FSO communication systems[6]. In CPolSK scheme, the requirement of polarization coordinates alignment is canceled and the complexity of system configuration has no significant increase. CPolSK modulation has about 3 dB lower signal-to-noise ratio (SNR) requirement than OOK in weak fluctuations[6].

Spatial diversity is a promising solution to mitigate atmospheric fades[7]. Using multiple apertures at the transmitter and/or receiver, spatial diversity has the potential for fading compensation with their inherent redundancy. It significantly reduces the potential for temporary blockage of the laser beam by obstructions. This multiple-aperture designs allow the system to support longer distances and through heavier attenuation while achieving higher data rates. Kim *et al.*[7] measured the performance of a multiple-input multiple-output (MIMO) FSO and discussed the design on the transmitter spacing and spacing patterns. Andrews *et al.*[8] studied the bit-error rate (BER) for direct detection systems using an array of receiver apertures. Haas *et al.*[9] demonstrated that ergodic capacity scaled as the number of transmit apertures timed the number of receiver apertures for high SNR. Tsiftsis *et al.*[10] investigated the error performance of FSO systems for $K$-distributed atmospheric turbulence channels and discussed potential advantages of spatial diversity.

In this letter, we propose a FSO communication system with CPolSK modulation and diversity receivers. The FSO communication system utilizes the spatial diversity receivers to receive the binary signals which are modulated by the two rotation states of circle polarization. Considering gamma-gamma (GG) atmospheric channel fading model, we derive a closed-form BER expression for such a FSO scheme. The BER performance can be evaluated by some important parameters such as atmospheric conditions, link length, communication wavelength, receiver aperture size and the number of spatial diversity receiver. Finally, numerical results are further demonstrated the influence from these parameters on the FSO systems and show quantitatively the differences in behavior between various different parameters.

 

A FSO system is considered where the binary signal is transmitted via one aperture and received by $N$apertures

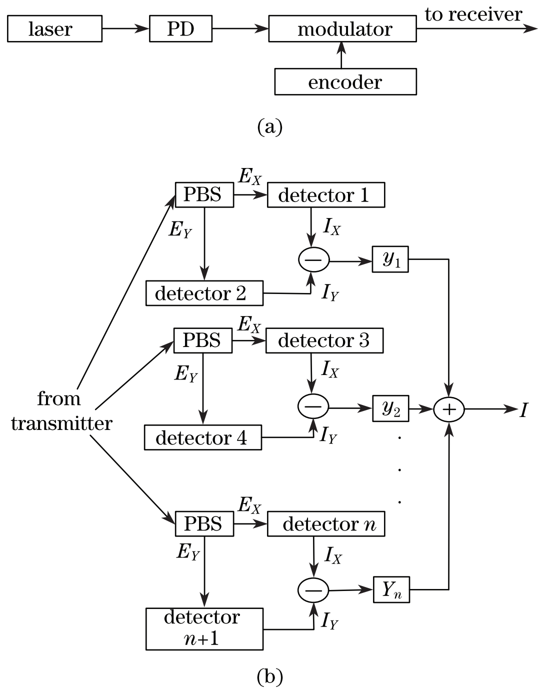


Fig. 1. Diagram of the FSO CPolSK communication system scheme (a) transmitter and (b) spatial diversity receiver. PD: polarization disk; PBS: polarizing beam splitter.

over a discrete-time ergodic channel with additive white Gaussian noise (AWGN). Specific to CPolSK, only two SOPs, left circle polarization for digital bit '0' and right circle polarization for '1', are selected and the information is transferred in a binary digital sequence. A diagram of the FSO communication system is presented in Fig. 1.

At the transmitter (see Fig. 1(a)), the polarization disk (PD) is used to get circular polarization light. The phase modulator with encoder generates the right and left circular polarization light representing binary code "0" and "1", respectively. At the receiver (see Fig. 1(b)), the optical signal is collected from $N$ apertures. Then it passes through $N$ polarizing beam splitters (PBS), which separate optical signal into $P$ and $S$ polarization. $E_X$ and $E_Y$ are the complex representations of the modulated signal in the parallel and perpendicular polarization states. Demodulator and detection are accomplished through a differential circuit. A linear combining method is used to combine the $N$ electrical signals and gain the summed output signal $I$ which is given by

$$I(t) = \begin{cases} A + n(t) & H = 1 \\ -A + n(t) & H = 0, \end{cases} \tag{1}$$

where $A$ is the average of the signal current $I$, $n(t)$ represents a AWGN with zero mean and variance $\sigma_n^2$. To simplify the analysis, BER is calculated as $P_{e,N} = P(0)P(1|0) + P(1)P(0|1)$, where $P(0)$ and $P(1)$ are the probabilities of transmitting "0" and "1", respectively, i.e., $P(0) = P(1) = 0.5$. In the absence of turbulence, the uncoded BER at the $n$th receiver aperture can be evaluated as

$$P_{e,N} = \frac{1}{2}\text{erfc}\Big(\frac{A}{\sqrt{2}\sigma_n}\Big), \tag{2}$$

where $\text{erfc}(x) = \big(2/\sqrt{\pi}\big) \cdot \int_x^{\infty} e^{-t^2}\text{d}t$ is error function.

We consider the coherence length of the optical beams is of the order of centimeters. The fading channels can be assumed as independent when the receiver apertures are placed a few centimeters apart. In order to fairly compare the spatial diversity receivers with the single receiver, the sum of $N$ receiver aperture areas has the same size with the area of single receiver. The summed output signal $I$ can be approximated by GG distribution. Therefore, the scintillation index is reduced by $N$ and can be expressed as $\sigma_{I,N}^2 = \sigma_{I,1}^2/N$[7], where $\sigma_{I,1}^2$ is the scintillation index for the single large-aperture receiver. Due to the present of optical turbulence, the signal current is the random variable and the probability of error is a conditional probability. Assuming the optical turbulence is GG distribution[7], the summed output signal $I$ can be expressed as[7]

$$p_{I,N}(u) = \frac{2(\alpha_N\beta_N)^{(\alpha_N+\beta_N)/2}}{\Gamma(\alpha_N)\Gamma(\beta_N)} u^{(\alpha_N+\beta_N)/2-1} K_{\alpha_N-\beta_N}(2\sqrt{\alpha_N\beta_N u}), u \geqslant 0, \tag{3}$$

where $u = i_{s,n}/E(i_{s,n})$ is the normalized summed signal with unit mean; $i_{s,n}$ is random variable of the summed signal current; $E(i_{s,n})$ denotes the average summed signal current; $K_m[\cdot]$ is the modified Bessel function of the second kind of order $m$; parameters $\alpha_N$ and $\beta_N$ which can be defined as $\alpha_N = \alpha_1(1 + N\beta_1)/(\beta_1 + 1), \beta_N = N\beta_1$[7], respectively, where parameters $\alpha_1$ and $\beta_1$ have the following expression for the spherical wave[7]:

$$\alpha_1 = \left[\exp\left(\frac{0.49\beta_0^2}{\left(1 + 0.18d^2 + 0.56\beta_0^{12/5}\right)^{7/6}}\right) - 1\right]^{-1}$$
$$\beta_1 = \left[\exp\left(\frac{0.51\beta_0^2(1 + 0.69\beta_0^{12/5})^{-5/6}}{\left(1 + 0.9d^2 + 0.62d^2\beta_0^{12/5}\right)^{5/6}}\right) - 1\right]^{-1}, \tag{4}$$

where $\beta_0^2 = 0.5C_n^2 k^{7/6} L^{11/6}$ is the Rytov variance, $d = \sqrt{kD^2/4L}$ is the receiver aperture, $k = 2\pi/\lambda$ is the optical wave number, $\lambda$ is the operation wavelength, $D$ the single receiver aperture diameter, $L$ is the link length, and $C_n^2$ is the refractive-index structure parameter which represents the turbulence condition.

In the presence of turbulence-induced scintillation, Eq. (2) is taken as a conditional probability density function (PDF). The uncoded BER of a CPolSK FSO system with $N$ receiver aperture is given by

$$\langle p_{e,N}\rangle = \frac{1}{2}\int_0^{+\infty} p_I(u) \cdot P_{e,N}\text{d}u, \tag{5}$$

where $E(\text{SNR}) = E(i_{s,N})/\sigma_n$ is the summed signal average SNR.

Using the following Meijer G functions in Ref. [11]:

$$\mathrm{erfc}(x) = \frac{1}{\sqrt{\pi}} G_{1,2}^{2,0}\left[x^2 \left| \begin{matrix} 1 \\ 0, \frac{1}{2} \end{matrix} \right.\right],\ K_\nu(x) = \frac{1}{2} G_{0,2}^{2,0}\left[\frac{x^2}{4} \left| \begin{matrix} - \\ \frac{\nu^2}{2}, -\frac{\nu^2}{2} \end{matrix} \right.\right], \quad (6)$$

then substituting Eqs. (2) and (3) into Eq. (5) and using the generalization of classical Meijer's integral from two G functions in Ref. [12], Eq. (5) is simplified as

$$\langle P_{e,N}\rangle = \frac{(\alpha_N\beta_N)^{(\alpha_N+\beta_N)/2}}{8\pi^{3/2}\Gamma(\alpha_N)\Gamma(\beta_N)} \times \left[\frac{E^2(\mathrm{SNR})}{2}\right]^{-(\alpha_N+\beta_N)/4}$$
$$\times G_{2,5}^{4,2}\left[\frac{(\alpha_N\beta_N)^2}{8E^2(\mathrm{SNR})} \left| \begin{matrix} -\frac{\alpha_N+\beta_N}{4}+\frac{1}{2}, -\frac{\alpha_N+\beta_N}{4}+1 \\ \frac{\alpha_N-\beta_N}{4}, \frac{\alpha_N-\beta_N}{4}+\frac{1}{2}, -\frac{\alpha_N-\beta_N}{4}, \\ -\frac{\alpha_N-\beta_N}{4}+\frac{1}{2}, -\frac{\alpha_N+\beta_N}{4} \end{matrix} \right.\right]. \quad (7)$$

Note that Meijer G function is a standard built-in function in most of the well-known mathematical software packages such as Mathematic and Maple. Thus, using the closed-form expression and the proper mathematical software packages, we can evaluate the BER performance of the FSO CPolSK systems with spatial diversity receivers. Moreover, Eq. (7) is taking into some important parameters, such as atmospheric conditions parameter $C_n^2$, link length $L$, communication wavelength $\lambda$, receiver aperture size $D$, and number of spatial diversity receivers $N$, and consequently can be used to simulate a specific FSO system.

Using Eq. (7), we investigate the BER performance of a FSO CPolSK system over atmospheric turbulence channels with the effects of atmospheric conditions parameter $C_n^2$ , link length $L$, communication wavelength $\lambda$, receiver aperture size $D$ and number of spatial diversity receivers $N$. In the analysis below, we evaluate the BER performance as a function of the average SNR for different system parameters and show quantitatively the differences in behavior between these different parameters. We consider two typical values of communication wavelength $\lambda$ ($\lambda$ =850 and 1 550 nm), two values of link length $L$ ($L$=1 000 and 6 000), and two values of the single receiver aperture diameter $D$ ($D$=0.01 and 0.08 m). We also take into account two different atmospheric conditions parameter $C_n^2$ ($C_n^2$=6.5 × $10^{-15}$ and 6.5 × $10^{-14}$ $\mathrm{m}^{-2/3}$). The results are shown in Figs. 2–6.

In Fig. 2, we present the average BER of the FSO system with the number of spatial diversity receivers $N = 1, 2, 6$, as a function of the average SNR $E$(SNR). In this case, we assume the communication wavelength $\lambda$=850 nm, the link length $L$=1 000, the single receiver aperture diameter $D$=0.01 m, and atmospheric conditions parameter $C_n^2 = 6.5 \times 10^{-15}$ $\mathrm{m}^{-2/3}$. It is obvious that the average BER is significantly improved as the number of spatial diversity receivers $N$ increases. In Fig. 3, just changing the communication wavelength from 850 to 1 550 nm, we can see that the FSO system with $\lambda$=1 550 nm can realize the lower BER performance than the one with $\lambda$=850 nm.

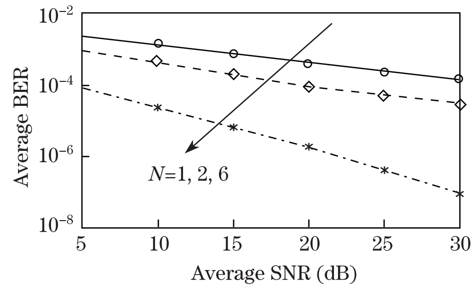


Fig. 2. Average BER versus average SNR for three values of $N$, assuming $\lambda$=850 nm, $L$=1 000, $D$=0.01 m, and $C_n^2 = 6.5 \times 10^{-15}\mathrm{m}^{-2/3}$.

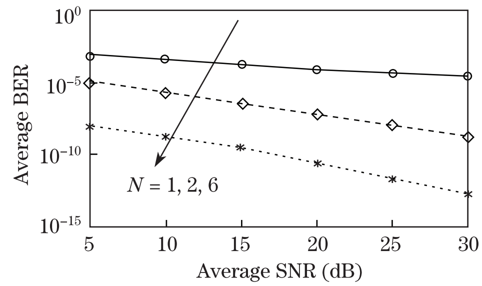


Fig. 3. Average BER versus average SNR for three values of $N$, assuming $\lambda$=1 550 nm, $L$=1 000, $D$=0.01 m, and $C_n^2 = 6.5 \times 10^{-15}\mathrm{m}^{-2/3}$.

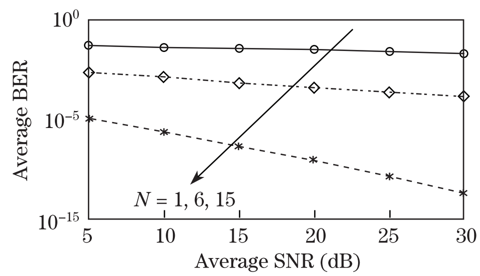


Fig. 4. Average BER versus average SNR for three values of $N$, assuming $\lambda$=1 550 nm, $L$=6 000, $D$=0.01 m, and $C_n^2 = 6.5 \times 10^{-15}\mathrm{m}^{-2/3}$.

Considering the longer link length $L$=6 000 in Fig. 4, we can see that even the link length becomes longer, the BER performance can be improved by increasing the number of spatial diversity receivers $N$. When $N$=15, it can be obtained an increament in average SNR about 90 dB with respect to $N$=1 at a target $\langle P_{e,N}\rangle = 10^{-9}$.

Furthermore, we analyze how the average BER is affected by the changes of atmospheric conditions parameter $C_n^2$. We consider $C_n^2 = 6.5 \times 10^{-14}\mathrm{m}^{-2/3}$ for strong turbulence conditions. The results are shown in Fig. 5. It is seen that the BER performance strongly depends on the atmospheric turbulence strength and as the number of spatial diversity receivers increasing this influence becomes weaker. In Fig. 6, we consider the larger single receiver aperture diameter $D$=0.08 m. It is obvious that increasing the single receiver aperture diameter $D$=0.08 m can easily make the FSO system achieve the target of $\langle P_{e,N}\rangle = 10^{-9}$ with the less $N$ by comparing with the smaller single receiver aperture diameter $D$=0.01 m.

In conclusion, we consider a FSO system scheme with CPolSK modulation and spatial diversity receivers. We

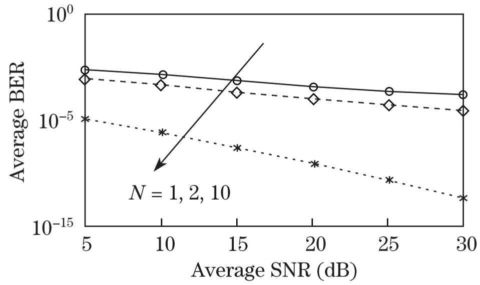


Fig. 5. Average BER versus average SNR for three values of $N$, assuming $\lambda$=1 550 nm, $L$=1 000, $D$=0.01 m, and $C_n^2 = 6.5 \times 10^{-14} \text{m}^{-2/3}$.

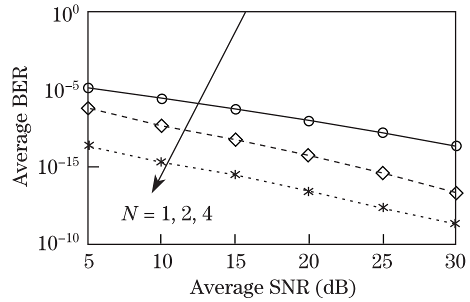


Fig. 6. Average BER versus average SNR for three values of $N$, assuming $\lambda$=1 550 nm, $L$=1 000, $D$=0.08 m, and $C_n^2 = 6.5 \times 10^{-15} \text{m}^{-2/3}$.

develop a closed-form BER expression for characterizing the performance of the FSO system under the atmospheric turbulence channels modeled by GG distribution. We study the effects from some important system parameters, such as atmospheric conditions, link length, communication wavelength, receiver aperture size, and number of spatial diversity receivers. Furthermore, we investigate some typical system parameters for the analysis of this FSO system and conclude that the FSO system scheme can improve the BER performance with the simple structure, low cost and high reliability. These results can be helpful for designing the FSO systems.

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