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Employing circle polarization shift keying in free space optical communication with gamma–gamma atmospheric turbulence channel

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A B S T R A C T

A novel theoretical model of a circular polarization shift keying (CPolSK) system for free space optical links through an atmospheric turbulence channel, is proposed. Intensity scintillation and phase fluctuation induced in atmospheric turbulence, from weak to strong levels, are specifically researched with respect to circular polarization control error caused by the system design. We derive closed form expressions of the bit error rate (BER) and outage probability for evaluating the BER performance and communication interruption in the Gamma–Gamma distributed channel model. Simulation results show that atmospheric turbulence and circular polarization control error have significant effects on the BER performance and interruption of communication in the CPolSK system. The deterioration in BER performance, caused by intensity scintillation and phase fluctuation, is augmented by the power penalty conditioned by the circular polarization control error. This consequently adds to the demand for emissive power from the CPolSK system. Furthermore, we demonstrate that controlling the circular polarization control error below 8° as well as the normalized threshold within 8 dB, 9 dB and 10 dB in turbulent scenarios from weak to strong levels can significantly reduce the probability of communication interruption occurring. This study provides reference material for further design of the CPolSK system.

1. Introduction

Recently, there has been a resurgence of research interest in free-space optical (FSO) communication for its advantages of greater bandwidth, higher data transmission rates, more compact equipment, faster link installation, lower power consumption and better security over radio frequency (RF) communications [1]. However, the most significant problem is that FSO links suffer from random changes in the refractive index caused by variations in air temperature and pressure [2,3], which lead directly to intensity scintillation and phase fluctuation [4]. This impairment, measured by the scintillation index (*SI*) [5] and phase noise [6], will severely reduce the beam quality, resulting in high error rates and greater probability of interrupted communication, seriously affecting the stability and reliability of the FSO communication system and significantly restricting further development of the FSO technology.

Polarization shift keying (PolSK) has been proposed to partially alleviate the restrictions of atmospheric turbulence [7,8,9]. This modulation uses the vectorial property of light waves and coding digital bits as different states of polarization, which can be well preserved in long FSO links, to effectively overcome the phase noise of the laser source and relatively improve the performance of the BER [8,9]. However, the PolSK modulation scheme, based on linear polarization, requires the alignment of the polarization coordinates of the transmitter and the receiver [10], which makes it difficult or even impossible to meet or guarantee the system performances of the FSO systems installed on moving objects, because of the random uncertainty of movement [11]. On this basis, Zhao Xinhui proposed circle polarization shift keying (CPolSK) modulation to improve the system performances by coding digital bits on two rotation states of circle polarization, namely, left-handed circular and right-handed circular [11,12]. Because of the symmetry of the rotational properties of circular polarization states and their small variations in atmospheric turbulence [11], FSO systems with CPolSK modulation can work normally for platforms with relative movements while achieving high immunity to the atmospheric turbulence.

In previous research on CPolSK in the FSO field [10–14], most was focused on the effects of the physical characteristics of turbulent atmosphere on the degree of polarization [11] and attenuation of the link [13] to prove the capability of CPolSK, while some was limited to studies of BER performance considering only the scintillation intensity but not under all turbulent scenarios (weak, moderate and strong) without phase fluctuation [11,14].

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Background noise and photodetector inherent noise were taken into account in Ref. [10], but the major noises from phase noise caused by the laser line width and turbulent atmosphere were ignored. In this study, the Gamma–Gamma distribution channel model [3] that is suitable for the description of all turbulent scenarios from weak to strong, was chosen to study the effects of both intensity scintillation and phase fluctuation caused by atmospheric turbulence on the proposed CPolSK system, with special consideration of the circular polarization control error caused by the system design. Moreover, the closed form expressions for the BER and outage probability were derived to evaluate the BER performance and communication interruption. In addition, we also took account of intensity scintillation and phase fluctuation effects in various turbulent scenarios on the BER performance from the perspectives of averaged signal-to-noise ratio (SNR) and averaged received optical power, and also of the communication interruption from the perspectives of the normalized threshold and angle range of the circular polarization control error. The performance advantages of the proposed CPolSK scheme were obtained through comprehensive comparisons with the traditional OOK scheme.

This paper is organized as follows. Section 2 describes the CPolSK system model. Section 3 gives the theoretical analyses of the BER performance and outage probability based on CPolSK modulation. Section 4 is devoted to simulation and numerical analysis with discussion. Section 5 states the conclusions of this work.

2. Circle polarization in FSO communications

2.1. Turbulence model

Intensity scintillation and phase fluctuation caused by atmospheric turbulence on the laser beam has a severe influence on degrading the sensitivity of the receiver. Because a Gamma–Gamma channel model can model the irradiance of FSO channels in all turbulent scenarios from weak to strong, it was chosen for this study. It should be noted that multipath scattering was ignored in this study.

The probability distribution model for intensity scintillation caused by an optical wave propagating in turbulent atmosphere accords with Gamma–Gamma distribution, therefore, the edge distribution of the received intensity scintillation I can be approximated as a Gamma–Gamma distribution, which is expressed as [3]

$$f(I)=\frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)}I^{(\alpha+\beta-2)/2}K_{\alpha-\beta}(2\sqrt{\alpha\beta I}),\quad I>0, \tag{1}$$

where $K_n(\cdot)$ is the modified Bessel function of the second order n, and $\Gamma(\cdot)$ is the gamma function. The large- and small-scale intensity scintillations of an optical wave are characterized by the positive parameters α and β, which are given by Ref. [1]

$$\alpha=\{\exp[0.49\delta_R^2/(1+1.11\delta_R^{12/5})^{7/6}]-1\}^{-1},$$

$$\beta=\{\exp[0.51\delta_R^2/(1+0.69\delta_R^{12/5})^{5/6}]-1\}^{-1}, \tag{2}$$

where $\delta_R^2=1.23C_n^2k^{7/6}L^{11/6}$ is the unitless Rytov variance used to classify the strength of intensity scintillation caused by atmospheric turbulence, C_n^2 stands for the altitude-dependent index of the refractive structure parameter, $k=2\pi/\lambda$ is the wave number, λ is the wavelength and L is the propagation distance. It is noted that the intensity scintillation is weak with $\delta 2R<1$, while the moderate intensity fluctuation is defined by $\delta 2R\cong 1$ and the strong intensity scintillation occurs when $\delta 2R>1$ [1]. Moreover, according to α and β, the scintillation index (SI) is defined as [9]:

$$SI=\frac{1}{\alpha}+\frac{1}{\beta}+\frac{1}{\alpha\beta}. \tag{3}$$

Perturbation approximation theory [4] derived by Tatarskii based on the theory of Rytov is a widely accepted theory on phase fluctuation. According to his theory, the distribution of the phase fluctuation can be described as a Gaussian distribution [9]. Furthermore, the phase noise arising from a turbulent atmosphere is random because of the random inhomogeneities along the propagation path. The probability density function for random noise can be described by a zero-mean Gaussian distribution [4]. Note that the effect of phase noise on the laser line width satisfies a Gaussian distribution [15], so the distribution of phase noise can be described as

$$f_\varphi(\varphi)=\frac{1}{\sqrt{2\pi}\delta}e^{-\varphi^2/2\delta^2}, \tag{4}$$

where δ^2 is the variance of the phase noise.

According to Olga Korotkova et al. [2], the degree of polarization (DOP) returns to its initial value (the value it has in the source plane) after propagating over a sufficiently long distance in a turbulent atmosphere. Moreover, Xinhui Zhao et al. also demonstrated that the state of polarization (SOP) remained unchanged and the DOP slightly increased to no more than 0.6% on propagation in a turbulent atmosphere [11]. Thus, SOP and DOP are considered controllable in this study, and only the effects of intensity scintillation and phase fluctuation on the system performance based on the circle polarization control error will be analyzed.

2.2. CPolSK system model

An optical communication system with CPolSK modulation based on Gamma–Gamma atmospheric turbulence channel is illustrated in Fig. 1.

The laser beam emitted by the LD is linearly polarized at an angle of 45° by the PC [8] with respect to the reference axis of the transmitter after the collimator. The linearly polarized beam is then phase modulated with different data, after being split into $\hat{x}$- and $\hat{y}$-polarization light, by launching into a PBS before being fed into the PBC, in which process the SOP of each path is adjusted by a PC to orient the SOPs of the two paths orthogonally to each other. This also yields the SOPs of $\hat{x}$- and $\hat{y}$-polarization with equal amplitude and zero phase differences. Thereafter, we adjust the angle between the two orthogonal axes of QWP and the propagating directions of the two lights to be 45° [12] to make the two linearly polarized lights into left- and right-handed circularly polarized light after QWP, respectively. Hence, the modulated information is finally sent to free space by E-A as left-handed circularly polarized light and right-handed circularly polarized light.

Here, we assume that the PMs are both linear as reported in Ref. [16] and that the channel is the ideal additive white Gauss noise (AWGN) channel. The emitted optical field $\overrightarrow{E_s(t)}$ is thus given as

$$\overrightarrow{E_s(t)}=\sqrt{\frac{P_s}{2}}e^{j(w_st+\varphi_s)}\left\{e^{j\phi_x}\hat{x}+je^{-j\phi_y}\hat{y}\right\}, \tag{5}$$

where P_s, w_s and φ_s are the optical power, angular frequency and the laser phase noise of the transmitted optical carrier, ϕ_x and ϕ_y are the phases modulated to the different polarization components of the beam with $\{\phi_x,\phi_y\}=\{0,\pi\}$, respectively. According to the rules of the codes fed into the modulators, namely, the phase does not change when entering "0" while the phase changes when entering "1", thereby producing the right- and left-handed circular polarized light by changing $\Delta\phi=\phi_y-\phi_x=\pi$ or 0 so that the phase