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Performance of wireless optical communication systems under polarization effects over atmospheric turbulence

Jiankun Zhang, Ziyang Li, Anhong Dang *

State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronics, Peking University, Beijing 100871, China

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A B S T R A C T

It has been recntly shown that polarization state of propagation beam would suffer from polarization fluctuations due to the detrimental effects of atmospheric turbulence. This paper studies the performance of wireless optical communication (WOC) systems in the presence of polarization effect of atmosphere. We categorize the atmospheric polarization effect into polarization rotation, polarization-dependent power loss, and phase shift effect, with each effect described and modeled with the help of polarization–coherence theory and the extended Huygens–Fresnel principle. The channel matrices are derived to measure the cross-polarization interference of the system. Signal-to-noise ratio and bit error rate for polarization multiplexing system and polarization modulation system are obtained to assess the viability using the approach of M turbulence model. Monte Carlo simulation results show the performance of polarization based WOC systems to be degraded by atmospheric polarization effect, which could be evaluated precisely using the proposed model with given turbulent strengths.

1. Introduction

Wireless optical communication (WOC) is increasingly being accepted as a technology supporting high bandwidth, broadband wireless applications over unlicensed optical wavelengths [1]. To date, the polarization state of a laser beam has been widely focused and utilized which provides a means for information transfer in WOC systems, such as polarization modulation system [2] and polarization multiplexing system [3]. Polarization modulation, also known as polarization shift keying (POLSK), stands as a novel modulation technique due to its immunity to phase noise and efficiency for operation over long distances [4]. To fully expand the capacity and spectral efficiency of an optical link, the polarization multiplexing is also widely used in WOC systems [5,6], where data are carried on orthogonal polarization states of the electric field.

Atmospheric turbulence is a key challenge to a practical WOC link resulting in the distortion of beam. To analyze the performance of WOC system, the effects of atmospheric turbulence should be considered. Besides the well-studied scintillation effect [7,8], recent studies show that the atmospheric turbulence also causes alteration of polarization states upon transmission [9–15]. In [9], the degree of polarization (DOP) of a laser beam is studied by applying the unified theory of polarization and coherence. A closed-form expression for DOP was given in [10], presenting results of a partially coherent beam modulated by a random anisotropic phase screen; and the DOP change through a space-to-ground channel is measured in [11]. [12] studies the polarization angle fluctuations, derives the distribution of polarization angle fluctuation and its variance linked with turbulent strength. [13] has concentrated on the variations of the Stokes parameters of different beams propagating in turbulence. In [14], the complete polarization state of laser beam with two wavelengths is measured in a turbulence-controlled channel; and the theoretical derivation of polarization parameters is presented in [15]. It shows that many polarization parameters including the Stokes parameters, the DOP, azimuth, and ellipticity all suffer from atmospheric effect. When analyzing the polarization-based FSO systems, the polarization effect should be also involved, because it could introduce crosstalk between orthogonal polarization states along the transmission path. However, most of the current works are concentrated on the optical propagation issue of atmospheric turbulence, and the impact of atmospheric polarization effect on communication is seldom discussed.

In this work, we study the performance of two general polarization-based WOC systems, i.e., polarization modulation and polarization multiplexing WOC systems, in the presence of polarization fluctuations of atmospheric turbulence. We summarize the atmospheric polarization fluctuations as three major effects: the polarization rotation effect, the polarization-dependent power loss and the polarization-dependent phase shift. For each consequence, the polarization changes are derived using the extended Huygens–Fresnel principle and polarization–coherence theory. The closed form expressions of bit error rate (BER)

* Corresponding author.
E-mail address: ahdang@pku.edu.cn (A. Dang).

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are then derived. Monte Carlo simulations show that the atmospheric polarization effect is not negligible under strong fluctuations.

This paper is organized as follows. Section 2 presents the channel model and summarizes the atmospheric polarization effect for a practical WOC system. The theoretical expressions of polarization-based WOC systems are then derived in Section 3. Monte Carlo simulation and results are presented in Section 4. Finally, Section 5 shows the discussion and conclusions.

2. Channel model

2.1. Polarization channel matrix

In the WOC systems, both the source property and turbulence coherence property will govern the signal's polarization change. The channel-induced polarization effect appears as the cross-polarization interference at the receiver. Since the free-space channel is linear, the channel property can be represented by the 2×2 polarization channel matrix given by [16]

$$\mathbf{H_p}(\omega) = \begin{bmatrix} H_{xx}(\omega) & H_{yx}(\omega) \\ H_{xy}(\omega) & H_{yy}(\omega) \end{bmatrix}. \tag{1}$$

By defining the polarization channel matrix, the Fourier transform of the electric field at the output of the FSO channel $E_r(\omega) = F\{E_r(t)\} = \mathbf{H_p}(\omega)E_s(\omega)$ may be expressed as

$$E_r(\omega) = \begin{bmatrix} E_{rx}(\omega) \\ E_{ry}(\omega) \end{bmatrix} = \begin{bmatrix} H_{xx}(\omega) & H_{yx}(\omega) \\ H_{xy}(\omega) & H_{yy}(\omega) \end{bmatrix} \begin{bmatrix} E_{sx}(\omega) \\ E_{sy}(\omega) \end{bmatrix}. \tag{2}$$

For a practical communication system, the polarization effect in the atmospheric channel can be divided into three aspects: the polarization rotation effect that rotates the polarization axis for a small angle $\Delta\theta$, the polarization-dependent power loss that induces different intensity loss in x- and y-polarizations, and the polarization-dependent phase shift that brings a phase difference $\Delta\varphi$ between polarizations. Considering the general polarization effect in the channel, the received signal in x- and y-polarizations can be then written as

$$\begin{aligned} E_{rx} &= \eta_x(E_{sx}\cos\Delta\theta - E_{sy}\sin\Delta\theta)e^{j\Delta\varphi/2}, \\ E_{ry} &= \eta_y(E_{sx}\sin\Delta\theta + E_{sy}\cos\Delta\theta)e^{-j\Delta\varphi/2} \end{aligned} \tag{3}$$

where η_x and η_y are the power losses in x- and y-polarization respectively. By substituting (3) into (2), the 2×2 channel matrix could be represented as

$$\mathbf{H_p}(\omega) = \begin{bmatrix} \eta_x\cos\Delta\theta e^{j\Delta\varphi/2} & -\eta_x\sin\Delta\theta e^{j\Delta\varphi/2} \\ \eta_y\sin\Delta\theta e^{-j\Delta\varphi/2} & \eta_y\cos\Delta\theta e^{-j\Delta\varphi/2} \end{bmatrix}. \tag{4}$$

In the following subsections, we evaluate the three polarization parameters in free space and present closed-form expressions of these parameters related with source property and turbulent strengths.

2.2. Polarization rotation effect

The polarization rotation effect is measured by rotation angle $\Delta\theta = \theta(z) - \theta(0)$, where $\theta(0)$ and $\theta(z)$ denote the polarization angle at the source and receiver plane respectively. $\theta(z)$ is defined as [12]

$$\theta = \arctan\left(\left|E_y\right| / \left|E_x\right|\right), \tag{5}$$

where E_x and E_y denote the electric field of x- and y-polarizations at any point. With the help of polarization–coherence function $W_{\alpha\beta} = \left\langle E_\alpha E_\beta^* \right\rangle$ where each of the suffixes α and β can be either x or y [17], the polarization angle θ can be further written as

$$\theta = \arctan\sqrt{W_{yy}/W_{xx}}. \tag{6}$$

For a linear polarized, partially coherent Gaussian beam, the polarization–coherence function at the source plane can be written as [18]

$$W_{\alpha\beta}(r_1, r_2, 0) = \frac{A_\alpha A_\beta}{2w^2}\exp\left[-\frac{r_1^2 + r_2^2}{w^2} - \frac{(r_1 - r_2)^2}{2\sigma_{\alpha\beta}^2}\right], \tag{7}$$

where k is wavenumber; $\alpha, \beta = x$ or y, A_x and A_y are the initial amplitudes of x- and y-polarizations respectively; w is the width of a Gaussian beam; $\sigma_{\alpha\beta}$ is the spatial coherence width of the beam. Following the extended Huygens–Fresnel principle [19], the field at any point in the half-space $L > 0$ into which the beam is assumed to propagate and which contains the turbulent atmosphere can be expressed by

$$\begin{aligned} W_{\alpha\beta}(r_1, r_2, L) = \frac{k^2}{4\pi^2 z^2} \iint \iint W_{\alpha\beta}(\rho_1, \rho_2, 0)\exp\Bigg[\frac{jk}{2z}(\rho_1 - r_1)^2 \\ - \frac{jk}{2z}(\rho_2 - r_2)^2 - \frac{1}{\rho_0^2}(\rho_1 - \rho_2)^2\Bigg] d^2\rho_1 d^2\rho_2, \end{aligned} \tag{8}$$

where $\rho_0 = \left(0.545C_n^2 k^2 L\right)^{-3/5}$ is the atmospheric coherence length [15], in which k is the wave number and C_n^2 is the structure constant of atmospheric turbulence. The physical meaning of (8) is the sum of spherical waves originating in the initial plane that arrives at the point (r_1, r_2, L). Substituting (7) into (8), the on-axis polarization correlation function at the receiver plane can be obtained as

$$W_{\alpha\beta} = \frac{A_\alpha A_\beta}{2w^2}\left[1 + \left(1 + \frac{w^2}{\sigma_{\alpha\beta}^2} + \frac{2w^2}{\rho_0^2}\right)\left(\frac{2L}{kw^2}\right)^2\right]^{-1}. \tag{9}$$

Moreover, according to the Rytov perturbation theory, the fluctuation of polarization angle follows Gaussian distribution given by [12]

$$f_\Theta(\Delta\theta) = \frac{1}{\sqrt{2\pi}\sigma_\theta}\exp\left(\frac{-\Delta\theta^2}{2\sigma_\theta^2}\right), \tag{10}$$

where

$$\sigma_\theta = \frac{\sigma_n \lambda L^{1/2}}{2\pi^{3/4} l^{3/2}} \tag{11}$$

is the root mean square (RMS) of $\Delta\theta$, with $\sigma_n = \left\langle \Delta n^2 \right\rangle^{1/2}$ the RMS of refractive index and l the scale factor.

2.3. Polarization-dependent power loss

Since atmospheric turbulence is anisotropic, the longitudinal wind velocity associated with the turbulent atmosphere fluctuates randomly about its mean value, leading to different changes of refractive indexes in horizontal and vertical directions. When polarized light passes through the turbulent atmosphere, intensities on the two orthogonal polarizations are impacted differently, resulting in the variations of the optical power portions for the two orthogonal signals, known as the power-dependent power loss of the beam. This effect could be measured through the power split ratio, defined as the power portion of x-polarization to the total power at the receiver plane given by

$$R = \left(\frac{\eta_x}{\eta}\right)^2 = \frac{\left|E_x\right|^2}{\left|E_x\right|^2 + \left|E_y\right|^2}, \tag{12}$$

which can be easily expressed by the polarization–coherence function written as

$$R = \frac{W_{xx}}{W_{xx} + W_{yy}}. \tag{13}$$

By substituting (9) into (13), the closed-form expression of power split ratio related with turbulent strength is obtained. Since the total power loss satisfies $\eta^2 = \eta_x^2 + \eta_y^2$, then the practical attenuations in two polarizations can be treated as power split effect (polarization-dependent part) over a common attenuation (polarization-independent part), which are $\eta_x = \eta\sqrt{R}$ and $\eta_y = \eta\sqrt{1-R}$ respectively. Since η is independent of polarization, it will be considered as a constant link loss in our further analysis.