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A key technology for standardizing outdoor optical wireless communications☆,☆☆

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Abstract

In this paper, we introduce a key technology, polarization modulation (PM), which should be taken into account when standardizing outdoor optical wireless communications (OWC), also known as free-space optical communications (FSO). We analyze the distortion of the polarization state when a laser beam propagates through the atmospheric channel. The floating range of the optical polarization was estimated and the necessity of researching the proposed technology was discussed. Moreover, we conducted a comparison between the PM-based FSO system and intensity modulation-based FSO system. The conclusions will be helpful in establishing the FSO standard architectures.

1. Introduction

The increasing demand for wider bandwidth and higher transmission speed has drawn attention to optical wireless communications (OWC), which use light as a carrier. Most of the existing OWC standards [1–5], shown in Table 1, apply to indoor systems.

Outdoor OWC, called free-space optical communications (FSO), is a line-of-sight technique that transmits optical signals through the atmospheric channel. Since the laser beam is inherently narrow, an FSO system has remarkable directivity and is available for ultra-long distance (>20 km) links. FSO devices are more portable and energy efficient than RF devices. When an optical fiber system is too expensive or impossible to set up (e.g., in natural disaster areas, mountainous areas, etc.), an FSO system can be an alternative option (10–20 km). An FSO system is also considered a solution to the last-mile problem (<10 km) [6–9]. In view of the advantages of the FSO system, the International Telecommunication Union has been developing FSO standards since 2006 [10].

The most studied FSO system is the intensity modulation (IM) scheme. In the report by [7,11–13], atmospheric turbulence strongly affected optical intensity and caused serious channel fading in IM-based FSO systems. On the other hand, the polarization state of the optical wave is a much more stable property when propagating though the atmospheric channel [14–21], which encouraged us to conduct research on PM-based FSO systems. PM can be roughly classified as linear polarization (LP) and circular polarization (CP) modulation. One kind of LP modulation scheme, called polarization shift keying (PolSK), defines two orthogonal polarization states as '1' and '0', respectively [15–19]. In paper [14], in order to take full advantage of polarization stability, another LP method – consecutive polarization modulation – which maps the signal into a consecutive optical polarization state, was applied to the FSO system. When standardizing mobile FSO systems, CP modulation is more suitable because the rotation of transceivers will cause angle misalignment. The most common CP modulation is circle polarization shift keying (CPolSK), which uses the

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Table 1
Existing OWC standards.

	Standards	Wavelength (nm)	Data rate
IEEE 802. 11		850–950	1 and 2 Mbps
IrDA	SIR	850–900	2.4–115.2 kbps
	MIR		0.576 and 1.152 Mbps
	FIR		4 Mbps
	VFIR		16 Mbps
	UFIR		96 Mbps
	Giga-IR		0.576 and 1.024 Gbps
VLCA	CP-1221	380–780	4.8 kbps
	CP-1222		
	CP-1223		
IEEE 802. 15. 7	PHY I	380–780	11.6–266.6 kbps
	PHY II		1.25–96 Mbps
	PHY III		12–96 Mbps

quarter wave plate to realize the mutual transformation between the linearly polarized states and circularly polarized states [8,9].

The purpose of this paper is to emphasize the importance of PM technology research in standardizing FSO systems. In Section 2, we analyze channel effects and estimate the floating range of both optical intensity and optical polarization. A comparison of the performance of PM-based and IM-based FSO systems is presented in Section 3. The results reflect the superiority of the PM scheme.

2. Channel model

2.1. Optical intensity

The Gamma–Gamma distribution model is widely accepted since it can represent both the weak and moderate-to-strong turbulence regions. It contains two Gamma distributed factors that modulate the scintillation and probability density function, which can be written as [6,11]

$$f_Q(Q) = \frac{2(\varepsilon\gamma)^{\frac{\varepsilon+\gamma}{2}}}{\Gamma(\varepsilon)\,\Gamma(\gamma)} Q^{\frac{\varepsilon+\gamma-2}{2}} K_{\varepsilon-\gamma}\left(2\sqrt{\varepsilon\gamma Q}\right), \quad Q = \frac{P_r}{\langle P_r\rangle} \tag{1}$$

where P_r is the received optical power, the symbol $\langle . \rangle$ denotes the ensemble average value over scintillation, and $K_m(.)$ is the modified Bessel function of the second kind of order m. ε and γ denote small- and large-scale factors, respectively, that can be expressed as [6,11]

$$\varepsilon = \left[\exp\left(\delta^2_{\ln A}\right) - 1\right]^{-1}, \tag{2}$$

$$\gamma = \left[\exp\left(\sigma^2_{\ln B}\right) - 1\right]^{-1}. \tag{3}$$

$\delta^2_{\ln A}$ and $\delta^2_{\ln B}$ are the small- and large-scale log-irradiance variances, respectively, that can be written as [6,11]

$$\delta^2_{\ln A} = \delta^2_{\ln A}(l_0) - \delta^2_{\ln A}(L_0), \tag{4}$$

$$\delta^2_{\ln B} = 0.51\delta^2_P\left(1 + 0.69\delta_P^{12/5}\right)^{-5/6} \tag{5}$$

where

$$\delta^2_{\ln A}(l_0) = 0.16\delta^2_{\Re}\left(\frac{\Im_{l_0}\Re_{l_0}}{\Im_{l_0} + \Re_{l_0}}\right)^{7/6} \cdot \left[1 + 1.75\left(\frac{\Im_{l_0}}{\Im_{l_0} + \Re_{l_0}}\right)^{1/2} - 0.25\left(\frac{\Im_{l_0}}{\Im_{l_0} + \Re_{l_0}}\right)^{7/12}\right], \tag{6}$$

$$\delta^2_{\ln A}(L_0) = 0.16\delta^2_{\Re}\left(\frac{\Im_{L_0}\Re_{L_0}}{\Im_{L_0} + \Re_{L_0}}\right)^{7/6} \cdot \left[1 + 1.75\left(\frac{\Im_{L_0}}{\Im_{L_0} + \Re_{L_0}}\right)^{1/2} - 0.25\left(\frac{\Im_{L_0}}{\Im_{L_0} + \Re_{L_0}}\right)^{7/12}\right], \tag{7}$$

$$\delta^2_P = 3.86\delta^2_{\Re}\left\{\left(1 + \frac{1}{\Re^2_{l_0}}\right)^{11/12}\left[\sin\left(\frac{11}{6}\arctan\Re_{l_0}\right) + \frac{1.51}{\left(1 + \Re^2_{l_0}\right)^{1/4}}\sin\left(\frac{4}{3}\arctan\Re_{l_0}\right) - \frac{0.27}{\left(1 + \Re^2_{l_0}\right)^{7/24}}\sin\left(\frac{5}{4}\arctan\Re_{l_0}\right)\right] - 3.5\Re_{l_0}^{-5/6}\right\}. \tag{8}$$

The related parameters are given by [6,11]:

$$\Re_{l_0} = \frac{10.89L}{kl_0^2}, \quad \Im_{l_0} = \frac{2.61}{1 + 0.45\delta^2_{\Re}\Re_{l_0}^{1/6}}, \quad \Re_{L_0} = \frac{64\pi^2 L}{kL_0^2}, \quad \Im_{L_0} = \frac{\Im_{l_0}\Re_{L_0}}{\Im_{l_0} + \Re_{L_0}}, \tag{9}$$

where l_0 is the inner scale of turbulence in the order from 1 mm to 10 mm, and L_0 is the outer scale of turbulence in the meter scale. The symbol $\delta^2_{\Re} = 1.23C_n^2 k^{7/6} L^{11/6}$ denotes the ***Rytov*** variance for a plane wave in which C_n^2 is the index of the refraction structure constant in the range 10^{-17} $m^{-2/3}$–10^{-13} $m^{-2/3}$, k denotes the optical wave number, and L is the transmission distance.

2.2. Optical polarization

2.2.1. Linear polarization distortion

The atmospheric channel is assumed to be homogeneous and isotropic, and the optical wave propagation follows the