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Bit error rate analysis with real-time pointing errors correction in free space optical communication systems

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ABSTRACT

Pointing errors caused by the atmospheric turbulence will degrade the performance of free space optical (FSO) communication systems, especially the bit error rate (BER). In this paper, we innovatively analyze the relationship between BER and pointing errors by the probability density functions (PDFs) and intensity displacement in focal plane under the On-Off Keying (OOK) modulation conditions. The closed-loop experimental system is set up in laboratory, where the fast steering mirror (FSM) is real-time controlled by embedded controller with the parallel processing technology and the atmospheric turbulence is simulated by a turbulence simulation box. The results of repeated experiments show that the method of pointing errors correction we proposed is efficient under the conditions of atmospheric turbulence. By utilizing our method, the BER can decrease from nearly 10^{-3} to nearly or even below 10^{-9}, thus improving the performance of FSO communication systems significantly.

1. Introduction

It is universally admitted that the research and commercial interest for free space optical communication systems is increasing rapidly, due to its low cost, wide bandwidth and no spectrum license requirements [1–7]. Since FSO communication systems usually have a narrow beam divergence angle, it is extremely sensitive to atmospheric turbulence and mechanical vibration [8–12]. Thus, pointing errors are induced [13,14]. As pointing errors have tremendous impact on BER, and BER is an important parameter in FSO communication systems, therefore, pointing errors correction is necessary [15,16].

Researches about the modified moment-matching estimation method have been made before [17]. Analytical expressions for the PDFs and moments of the received signal were developed and used to estimate the beam jitter and boresight. Meanwhile, the irradiance fluctuations due to atmospheric turbulence are taken into account. The pointing errors induced by jitter and boresight are analyzed in theory and numerical simulation. In those papers, the FSO communication systems are dealt with by using the intensity modulation/direct detection (IM/DD) with OOK modulation, the average capacity is analyzed with pointing errors in theory and numerical simulations [18–20]. The outage capacity performance of FSO optical links with pointing errors over atmospheric turbulence is analyzed by the model including the effect of beam width, detector size and jitter variance explicitly [21,22]. Similarly, the asymptotic error rate of FSO optical links with pointing errors over atmospheric turbulence is analyzed [23–25].

Recently, BER of FSO communication systems with pointing errors has been analyzed by different methods. Yang et al. [26,27] derive the BER of inter-satellite laser communication links with on-off-keying systems in the present of both wavefront aberrations and pointing errors, but excluding the noise factor of the detector. The BER performance with pointing errors and wave-front aberrations is analyzed in pupil plane in theory and numerical simulations in [26]. However, there is no compensation of the errors. In our paper, we are only concerned about the pointing errors, analyze the generation principle of pointing errors in focal plane, then the relationship between BER and pointing errors is given. The closed-loop experimental system is introduced in our paper, distinguished from the method in [26], we measure pointing errors in the focal plane by high speed camera. Fast steering mirror controlled by embedded controller in this paper is known as an efficient method to correct pointing errors in real time [28–30]. A turbulence simulation box is designed to simulate atmospheric turbulence. The results of repeated experiments show that the method of pointing errors correction we proposed is more efficient in weak turbulence conditions. BER performance can be reduced to nearly or even below 10^{-9}.

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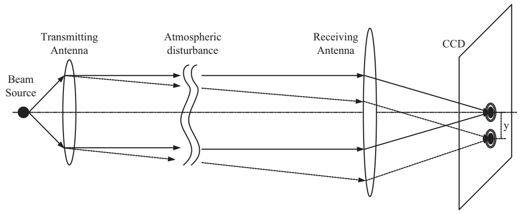

Fig. 1. Pointing errors schematic diagram.

2. Theoretical model

Due to the atmospheric turbulence, pointing errors are induced. Therefore it will increase BER. We assume pointing errors to be in azimuth and elevation directions, it can be shown in Fig. 1.

Pointing errors can be modeled as zero-mean Gaussian random variables [26]. The PDFs are given by:

$$f_{\mathrm{P}}(\phi_{\mathrm{A}})\sim N(0,\quad \sigma_{\mathrm{A}}) \tag{1}$$

$$f_{\mathrm{P}}(\phi_{\mathrm{E}})\sim N(0,\quad \sigma_{\mathrm{E}}) \tag{2}$$

where $N(0, \sigma)$ represent a normal distribution with mean zero and standard deviation (STD) σ. ϕ_{A} and ϕ_{E} are the angles of pointing errors in azimuth and elevation directions respectively. σ_{A} and σ_{E} are pointing STD in azimuth and elevation directions respectively.

The relationship between the pointing errors angles and the displacement in the focal plane of receiver terminal can be expressed as:

$$x = \phi_{\mathrm{A}} \cdot f \tag{3}$$

$$y = \phi_{\mathrm{E}} \cdot f \tag{4}$$

where x and y are the displacement on the focal plane of receiver terminal in x and y axes, respectively. f is the focal length.

According to Eqs. (3) and (4) and the character of PDFs, the displacement of (x, y) obeys $N(0, f\,\sigma)$ distribution. The PDFs of the displacements of receiver terminal are as shown:

$$f_{\mathrm{D}}(x) = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{A}} f} \exp\left(-\frac{x^2}{2\sigma_{\mathrm{A}}^2 f^2}\right) \tag{5}$$

$$f_{\mathrm{D}}(y) = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{E}} f} \exp\left(-\frac{y^2}{2\sigma_{\mathrm{E}}^2 f^2}\right) \tag{6}$$

Here we assume that the beam width at the receiver is a Gaussian wave, which is much smaller than the size of apertures. We only consider the pointing errors in this paper, then the optical field of transmitted beam in pupil plane $R(x_0, y_0)$ can be expressed as

$$R(x_0, y_0) = A \quad \exp\left(-\frac{x_0^2 + y_0^2}{\omega_0}\right) \text{pupil} \quad (x_0, y_0) \tag{7}$$

where A is a constant, ω_0 is the half width of the transmitted beam, pupil (x_0, y_0) is the pupil function.

$$\text{pupil} \quad (x_0, y_0) = \begin{cases} 1, & \text{if} \quad 0 \le \sqrt{x_0^2 + y_0^2} \le D/2 \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

where D is the receiving antenna diameter. According to the theory of Fraunhofer diffraction [31,32], the received intensity displacement in the focal plane can be expressed as:

$$I(x, y) = \frac{1}{\lambda^2 f^2}\left|\iint R(x_0, y_0) \exp\left(-ik\frac{x_0 x + y_0 y}{f}\right) \mathrm{d}x_0 \quad \mathrm{d}y_0\right|^2 \tag{9}$$

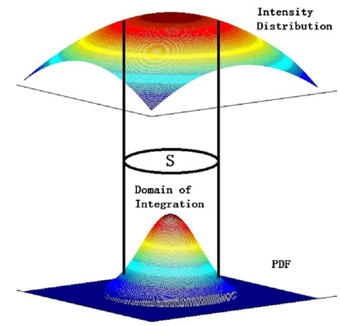

Fig. 2. The schematic diagram of the principle.

where λ is the wavelength, k is the wave number, and $k = 2\pi/\lambda$. Therefore, the intensity distribution in focal plane is airy disk similarly. Considering the received power in focal plane, the BER for On-Off Keying (OOK) modulation system is given by:

$$\mathrm{BER} = \frac{1}{2} P(I \le I_{\mathrm{T}}) \tag{10}$$

where I is the optical power received by the detector, $P(I \le I_{\mathrm{T}})$ is the probability of $I(x, y) \le I_{\mathrm{T}}$. According to the mechanism of OOK modulation, code "0" will not be misjudged if the noise of the detector is neglected. For the code "1", it will be misjudged as code "0" if the energy in the area $S = \{(x, y) : I(x, y) > I_{\mathrm{T}}\}$ is lower than the threshold. Here we assume that the pointing errors in azimuth and elevation directions are mutual independence. Then, Eq. (10) shall be rewritten as:

$$\mathrm{BER} = \frac{1}{2} - \frac{1}{2} \oiint_{\mathrm{s}} f_{\mathrm{D}}(x) f_{\mathrm{D}}(y) \mathrm{d}s \tag{11}$$

Substituting Eqs. (5) and (6) into Eq. (11), Eq. (11) can be expressed as:

$$\mathrm{BER} = \frac{1}{2} - \frac{1}{2} \oiint_{\mathrm{s}} \frac{1}{2\pi f^2 \sigma_{\mathrm{A}} \sigma_{\mathrm{E}}} \exp\left(-\frac{x^2}{2 f^2 \sigma_{\mathrm{A}}^2} - \frac{y^2}{2 f^2 \sigma_{\mathrm{E}}^2}\right) \mathrm{d}s \tag{12}$$

As the parameters f, σ_{A} and σ_{E} are given in Eq. (11), BER is determined by the integral area S, which is obtained by fiber diameter and the sensitivity of the receiver in focal plane. The schematic diagram of the principle is shown in Fig. 2. Therefore, the measurement of the displacement is crucial for evaluating BER.

To reduce the BER, pointing errors shall be measured and corrected in real time. In this paper, high speed near infrared Charge Coupled Device (CCD) camera is an effective instrument to measure the displacement. To correct the errors, FSM actuated by piezoelectric tip/tilt platform is used [33]. It is controlled by voltages, V_x and V_y. Here we mainly concern about the x direction in that there are no essential difference between the two directions. The deviation from the desired voltage value $V_x^{(0)}$ at nth iteration, the error of voltage $e_x^{(n)} = V_x^{(n)} - V_x^{(0)}$ determines the control signal $U_x^{(n)}$, by applying the Proportional-Integral (PI) control algorithm which is later discussed in this paper, which is shown as:

$$U_x^{(n)} = U_x^{(n-1)} + k_{\mathrm{P},x} e_x^n + k_{\mathrm{I},x} S_x^{(n)} \tag{13}$$

where $k_{\mathrm{P},x}$ is the proportional control parameters, $k_{\mathrm{I},x}$ is the integral control parameters. After iterations, the error integral $S_x^{(n)}$ is given by:

$$S_x^{(n)} = \alpha e_x^{(n)} + (1 - \alpha) S_x^{(n-1)} \tag{14}$$

where α is the update rate. Therefore, we can obtain the displacement by a high speed camera and real-time correct the errors, and then analyze the BER of system by Eq. (12).