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Bandwidth of adaptive optics system in atmospheric coherent laser communication

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ABSTRACT

The bit-error-rate performance of free space optical communication systems with binary phase shift keying modulation and coherent homodyne detection is performed. Besides the turbulence-induced wave-front phase error and the amplitude fluctuation, the servo bandwidth of adaptive optics system is investigated. It is shown that Greenwood frequency is large enough for the servo bandwidth of adaptive optics system when the detected photons per bit are more than 100. However, if the photons per bit are less than 70, the Greenwood frequency is only sufficient for weak scintillation. We should increase the servo bandwidth to almost twice the value of Greenwood frequency at least in order to obtain an acceptable BER performance when the scintillation index is larger than 0.7. In addition, we also investigate the aperture averaging effects when the receiving aperture is larger than the coherent length.

1. Introduction

Free space optical (FSO) communication is considered to be an alternative to radio-frequency (RF) links in long-range communication for its attractive features, such as much higher date rate, better security, and lower energy consumption. For satellite–satellite links, the FSO communication has been successfully verified by an optical 5.625 Gbps communication link based on homodyne binary phase shift keying (BPSK) [1]. However, for satellite–ground links, the FSO communication is challenged by the effects of atmospheric turbulence [2]. Amplitude fluctuation and wave-front aberration of the signal light are the main factors which can cause an extreme increase of bit error rate (BER). It is supposed that the adaptive optics (AO) is able to compensate the atmospheric wave-front aberration so as to improve the performance of FSO communication system [2,3]. Different levels of adaptive correction accompanied with amplitude fluctuation will lead to different performances of the communication system. This issue is very important in the FSO communication system design and has attracted more and more attention in recent years.

Compared to traditional direct detecting scheme, the coherent detection offers better receiver sensitivity and is able to obtain a much higher date rate [4]. However, system performance is more vulnerable to the effect of atmospheric turbulence, such as signal power scintillation and wave-front phase distortion. The mixing efficiency between the signal light and the local oscillator laser is easily to be degraded by wave-front phase distortion which has severe influence on the coherent detection system. Loss of single mode fiber coupling efficiency is another serious problem caused by wave-front phase aberration [2]. In view of this, adaptive optics is proposed to implement wave-front phase correction. On the other side, amplitude fluctuation of the receiving light is also a major factor which degrades performance of FSO communication system. In previous works, Belmonte et al. [5] proposed a mathematical model for signal light propagating through atmospheric turbulence and analyzed the effect of several factors, including turbulence strength and number of Zernike modes corrected by adaptive optics. In their mode modified Rician distribution is employed to define the probability density function (PDF) of amplitude. Zuo et al. [6] used this mode to investigate the BER performance of FSO communication links in weak non-Kolmogorov turbulence and showed that BER decreased sharply as more modes were corrected by adaptive optics. Considering the influence of both the amplitude fluctuation and spatial phase aberration, the mode is accurate when the ratio of receiving aperture diameter D to the coherent length r_0 is very large. Without the adaptive optics compensation in system, Niu et al. [7] analyzed the BER of the FSO communication for several kinds of modulation/detection schemes. Based on the assumption that the amplitude is homogeneous in the receiving aperture, Liu et al. [8] studied the adaptive correction to spatial phase error in FSO communication system performance. They demonstrated that the adaptive optics is a powerful way to promote BER performance. However, the

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temporal phase error caused by the time delay between the wave-front measurement and its correction also needs to be considered in FSO communication optics system. And the servo bandwidth of AO system needs to be analyzed in detail.

Considering the influence of amplitude fluctuation, adaptive correction to both the spatial and temporal phase errors is studied for homodyne BPSK links in this paper. BER performance against servo bandwidth of AO system is investigated and compared with the result of Greenwood frequency [9] for different strengths of atmospheric turbulence. The effect of both the adaptive optics correction and the aperture averaging effects (AAE) on the BER performance is evaluated for different strengths of scintillation. The probability density function (PDF) of the amplitude is described by Gamma–Gamma distribution which may be accurate for any fluctuation condition [10].

2. Coherent free-space optical receiver and terrestrial free-space optical links

2.1. Signal to noise ratio (SNR) of an optical homodyne receiving system

Assuming the signal light is plane wave, the field at the receiving pupil plane is expressed as [11]

$$\vec{E_S} = E_S(r,\theta)\exp[-i(\omega_s t + \phi_m + \phi_w(r,\theta)] \quad (1)$$

where $E_S(r,\theta)$ is the amplitude with random spatial distribution and magnitude fluctuation caused by the atmospheric turbulence, ω_s is the angular frequency of the signal light, ϕ_m denotes the encoded phase information, and $\phi_w(r,\theta) = \phi_p + \phi_n(r,\theta)$ is the turbulence-induced random wave-front phase error. Adaptive optics is only able to remove the high order wave-front phase aberration $\phi_n(r,\theta)$. The piston term ϕ_p, together with the encoded phase ϕ_m, constitute the signal phase.

The local oscillator (LO) laser field in single model fiber can be expressed as

$$\vec{E_{LO}} = E_{LO}(r,\theta)\exp[-i\omega_{LO}t + \phi_p] \quad (2)$$

ϕ_p in the local oscillator laser field is generated by the phase-locked-loop in order to compensate the piston term in the turbulence-induced phase front distortion. Before mixing with the signal beam in free space, the LO beam is been collimated by a lens and passed through a pinhole which is smaller than the beam waist. So we can assume the LO beam as a plane wave. After the two fields mix together, the converting power for a single point area at the receiving aperture can be expressed as

$$\begin{aligned} P &= (\vec{E_S} + \vec{E_{LO}})\cdot(\vec{E_S}^* + \vec{E_{LO}}^*) \\ &= P_S(r,\theta) + P_{LO} + 2E_S(r,\theta)E_{LO}\cos(\Delta\omega t + \phi_m + \phi_n(r,\theta)) \end{aligned} \quad (3)$$

where P_S and P_{LO} are the laser powers of the signal light and the local oscillator laser respectively. The photocurrent at the output of the detector is comprised of three parts

$$\begin{aligned} I(t) &= I_{dc} + I_{ac}(t) + n(t) \\ &= R(P_S(r,\theta) + P_{LO}) + 2RE_S(r,\theta)E_{LO}\cos(\Delta wt \\ &\quad + \phi_m + \phi_n(r,\theta)) + n(t) \end{aligned} \quad (4)$$

where $R = \eta e\lambda/hc$ is the responsivity of photodetector, e is the electronic charge, η is the quantum efficiency, h is the Planck constant, c is the light velocity and λ is the wavelength of the signal light. For a certain communication data rate Q, the number of photons per bit received is $\lambda P_S/hcQ$. In Eq. (4), $\Delta\omega$ is the beat frequency between the signal light and the local oscillator, and $n(t)$ is the shot noise. In a FSO system which is employed with $P_{LO} \gg P_S$, the direct-current (DC) power is mainly determined by local oscillator laser. The variance of the shot noise is $\sigma_n^2 = 2eR\Delta f P_{LO}$, where Δf is the noise equivalent bandwidth (NEB) of the photo-detector [11]. Photocurrent due to thermal noise and the dark current are negligible compared with that caused by RP_{LO}, which means the shot noise of the local laser is the major source of system noise. The encoded phase ϕ_m is zero or π which will not change the absolute value of the second part in Eq. (4). And $\Delta\omega t$ is extremely small when the phase-locked-loop technology is applied in the receiver, which is called homodyne detection. So the phase term in Eq. (4) is mainly determined by $\phi_n(r,\theta)$. The signal to noise ratio (SNR) at this optical receiving terminal is determined by the ratio of time average of the alternating-current (AC) power to the shot noise variance which can be defined by

$$\begin{aligned} \gamma &= \frac{\langle I_{ac}^2(t)\rangle}{\sigma_n^2} = \frac{2\eta\lambda[\iint E_s(r,\theta)E_{LO}\cos(\phi_n(r,\theta))rdrd\theta]^2}{hc\Delta f\iint E_{LO}^2 rdrd\theta} \\ &= \frac{2\eta\lambda[\iint E_s(r,\theta)\cos(\phi_n(r,\theta))rdrd\theta]^2}{hc\Delta f\cdot(\pi D^2/4)} \end{aligned} \quad (5)$$

In Eq. (5), $\langle\rangle$ means the time average and D is the diameter of the receiving aperture. Without the influence of atmospheric turbulence, the SNR of FSO system applying homodyne detection can be defined by

$$\gamma = \frac{2\eta\lambda P_S}{hc\Delta f} \quad (6)$$

In the receiving pupil plane, the amplitude and phase is randomly changed for each point area. Based on the approximation of speckle statistics [12], the receiving aperture can be divided into multitude of independent cells of diameter r_0. This parameter is the atmospheric coherent length, also called Fried's parameter, a measure of atmospheric turbulence strength

$$r_0 = [0.432\cdot k^2\cdot\sec\xi\cdot\int_{h_0}^{h} C_n^2(z)\cdot dz]^{-3/5} \quad (7)$$

where $k = 2\pi/\lambda$ is the wave number, ξ is the Zenith angle, z is the altitude in meters, h_0 is the altitude of the optical ground station, h is the altitude of the satellite, and $C_n^2(z)$ is the refractive-index structure parameter, which is a measure of the strength of the fluctuations in the refractive index [10]. One of the most widely used models for $C_n^2(z)$ is the Hufnagel-Valley (H-V) model

$$\begin{aligned} C_n^2(z) &= 0.00594(v/27)^2(10^{-5}z)^{10}\exp(-z/1000) \\ &\quad + 2.7\times10^{-16}\exp(-z/1500) + C_n^2(0)\exp(-z/100) \end{aligned} \quad (8)$$

where v is the root-mean-square wind speed (pseudowind) in meters per second [10], and $C_n^2(0)$ is the value of refractive-index structure parameter at the ground in $m^{-2/3}$.

The number of cells N can be approximated to $(D/r_0)^2$. The amplitude and wave-front phase fluctuation of the cells are independent to each other and the phase distribution can be considered to be a Gaussian function with a variance that decreases as the number of corrected Zernike polynomial increases [12].

Under such approximation, the average SNR can be expressed by

$$\gamma = \frac{2\eta\lambda}{hc\Delta f\cdot N^2}\iint\left[\sum_i^N E_{Si}\cdot\cos(\phi_{ni})\right]^2 p_a(E)p_\phi(\phi)dEd\phi \quad (9)$$

where $p_a(\cdot)$ and $p_\phi(\cdot)$ are the probability density function (PDF) of the amplitude and phase respectively.

According to the approximation of speckle statistics [12], the