Optics Communications 305 (2013) 185–189

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

BPSK based subcarrier intensity modulated free space optical system in combined strong atmospheric turbulence

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ARTICLE INFO

Article history:
Received 10 February 2013
Accepted 21 April 2013
Available online 16 May 2013

Keywords:
Free space optics
Bit error rate
Channel capacity
Outage probability
Subcarrier intensity modulation
Atmospheric turbulence

ABSTRACT

In this paper the performance of a free space optical (FSO) communication system is analyzed by considering heavy atmospheric losses such as scattering, absorption, channel fading and misalignment fading. For the analysis, subcarrier intensity modulated free space optical (SIM-FSO) communication system using binary phase shift keying (BPSK) is employed. The bit error rate (BER), channel capacity and outage probability of the radiated signal are then investigated over a *K*-distributed mutual slow fading turbulence channel with illustrative 2D and 3D plots. Novel closed-form analytical expressions are derived for the combined strong turbulent channel model, average BER, channel capacity and outage probability for the considered communication system.

1. Introduction

Free space optical (FSO) communication, a form of high speed wireless optical communication relies on pure line of sight (LOS) technology. Its performance strongly depends on the atmospheric conditions between the transmitter and receiver [1,2]. The foremost advantages of wireless optical communications are high bandwidth, high security and ease installation without license [3]. The key applications FSO communication includes inter- and intra-chip communication [4,5], inter-satellite communication [6,7], alternative technology for optical fiber networks [8], temporary network installation [9] and radio over FSO communications [10]. However, the major drawback of FSO is natural turbulence [11]. To improve the signal quality in the receiver side various channel models, modulation techniques and diversity techniques are used [16,25]. In general, the wireless channel is modeled as gamma–gamma [12,13], Rayleigh [14] or exponential channel model [15,16] among others. The performance of the FSO system is generally analyzed by computing the bit error rate (BER), outage probability and channel capacity [17,18].

In a recent work, [19], the optical channel has been systematically described using a mutual slow fading channel model. Its performance analysis parameters such as outage probability, channel capacity and the link impairments imposed by the atmospheric attenuation due to beam extinction were also evaluated. They also investigated the channel fading due to turbulence and pointing errors for an on–off keying FSO system. In another work, [20], the performance of a subcarrier intensity modulated free space optical (SIM-FSO) communication system was investigated over a *K*-distributed turbulence channel.

In this paper, the performance of SIM-FSO communication system using binary phase shift keying (BPSK) is investigated over a *K*-distributed mutual slow fading turbulence channel. Novel equations are derived for BER, outage probability and channel capacity for the considered system. The performance analysis and results are illustrated through 2D and 3D plots.

The paper is organized as follows: Section 2 discusses the SIM-FSO system model used in our work. In Section 3, the mutual channel fading model is discussed. In Section 4, expressions for average BER, channel capacity and outage probability for the considered system are derived and presented. Section 5 describes the numerical results with graphical analysis. Finally, concluding remarks are highlighted in Section 6.

2. BPSK based SIM-FSO communication system

The considered BPSK based SIM-FSO system with *K*-distributed turbulence channels is represented in Fig. 1. BPSK based subcarrier intensity modulated signal is transmitted through the channel, along with additive white Gaussian noise in the presence of beam extinction and pointing errors. In Fig. 1, the transmitted signal is scattered due to natural turbulence in the atmospheric channel (AC).

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http://dx.doi.org/10.1016/j.optcom.2013.04.056

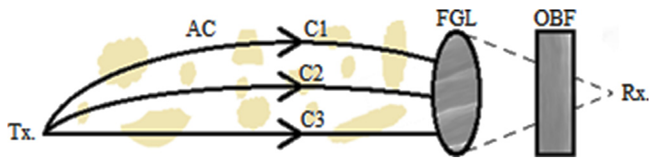

Fig. 1. Block diagram of communication system with *K*-distributed turbulence channels. AC: Atmospheric channel; OBF: Optical bandpass filter; FGL: Finite Gaussian lens; C1: Independent scatter component; C2: Coupled to LOS component; and C3: Line of sight (LOS) component.

These turbulences are caused by rain, fog, smoke, smog, heavy dust particles, etc. But heavy fog, as shown in Fig. 1, causes the maximum attenuation in the transmitted signal. In this work we consider strong atmospheric turbulence condition for the analysis of the FSO system. The scattered components and the LOS component are clearly shown in the figure. At the receiver, the signal (y) is detected via a finite Gaussian lens [21], expressed as

$$y = h\gamma P_{FSO}x + n \tag{1}$$

where h is the channel state, γ is the detector responsivity, x is the transmitted signal, n is the noise caused by various sources and P_{FSO} is the average optical transmitted power. The channel state h models the optical intensity fluctuations [2] resulting from atmospheric loss, turbulence and fading as

$$h = h_l h_s h_p \tag{2}$$

where h_l is the attenuation due to beam extinction and path loss, h_s due to scintillation effects and h_p due to the geometric spread and pointing errors.

The received electrical signal to noise ratio as considered in [22] is expressed as

$$SNR(h) = \frac{(\gamma h)^2}{2\sigma_n^2} \tag{3}$$

where σ_n^2 is the variance of the channel noise.

3. Channel models of FSO systems

The combined channel fading model that has been presented in [19] is derived with the combination of atmospheric turbulence induced fading and misalignment fading for both weak and strong atmospheric turbulence conditions.

For weak atmospheric turbulence conditions, the channel model expressed as the probability density function of the irradiance intensity, h as given by [19] is

$$f_h(h) = \frac{\xi^2}{(A_0 h_l)^{\xi^2}} h^{\xi^2-1} \times \int_{h/A_0 h_l}^{\infty} \frac{1}{h_s^{\xi^2+1}\sigma_I(D)\sqrt{2\pi}} \exp\left(-\frac{\left[\ln(h_s)+0.5\,\sigma_I{}^2(D)\right]^2}{2\sigma_I{}^2(D)}\right) dh_s \tag{4}$$

where $\sigma_I{}^2(D)$ is the aperture averaged scintillation index, $\xi = w_{z_{eq}}/\sigma_s$ is the ratio between the equivalent beam radius at the receiver and the pointing error displacement standard deviation at the receiver and A_0 is the fraction of the received power at zero radial distance.

For strong atmospheric turbulence conditions, the channel model expressed as the probability density function of the irradiance intensity, h as given by [19] is

$$f_h(h) = \frac{2\xi^2(\alpha\beta)^{(\alpha+\beta)/2}}{(A_0 h_l)^{\xi^2}\Gamma(\alpha)\Gamma(\beta)} h^{\xi^2-1} \times \int_{h/A_0 h_l}^{\infty} h_s{}^{(\alpha+\beta)/2-1-\xi^2} K_{(\alpha-\beta)}(2\sqrt{\alpha\beta h_s}) dh_s \tag{5}$$

where α and β are the effective numbers of large and small scale turbulent eddies, $\Gamma(\cdot)$ is the gamma function. $K_{(\alpha-\beta)}$ is the modified Bessel function of the second kind of order $(\alpha-\beta)$ which can be simplified using Meijer G function [23, Eq. (14)]. Then using [24, Eq. (07.34.21.0085.01)], a closed-form expression for the channel model is obtained, as proved in Appendix A and expressed by

$$f_h(h) = \frac{\alpha\beta\xi^2}{A_0 h_l \Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{3,0}\left[\frac{\alpha\beta h}{A_0 h_l}\Bigg|_{-1+\xi^2,\ \alpha-1, \beta-1}^{\xi^2}\right] \tag{6}$$

4. Performance analysis of proposed BPSK based SIM-FSO system

The performance of the considered system is evaluated on the basis of average BER, channel capacity and outage probability.

4.1. Bit error rate

In the considered SIM-FSO communication system, the subcarrier is pre-modulated using BPSK. By modulating the optical signal with radio frequency, the subcarrier provides SIM. For a coherent BPSK demodulator, the probability of conditional BER depending on the intensity fluctuation [25,26] is expressed as

$$P_{e/h}(h) = Q\left(\frac{h\gamma}{\sqrt{2}\sigma_n}\right) = 0.5 \times \text{erfc}\left(\frac{h\gamma}{2\sigma_n}\right) \tag{7}$$

where γ is the photo detector responsivity, σ_n^2 is the variance of the channel noise and $Q(\cdot)$ is the Gaussian Q function related to the complementary error function erfc($\cdot$) as $2Q(\sqrt{2}x) = \text{erfc}(x)$.

The probability of average BER for BPSK based SIM-FSO over K-distributed mutual slow fading turbulence channel can be achieved by using

$$P_e = \int_0^{\infty} P_{e/h}(h) f_h(h) dh \tag{8}$$

By using Eqs. (6) and (7) in (8), we get

$$P_e = \frac{\alpha\beta\xi^2}{A_0 h_l \Gamma(\alpha)\Gamma(\beta)} \times \int_0^{\infty} 0.5\,\text{erfc}\left(\frac{h\gamma}{2\sigma_n}\right) \times G_{1,3}^{3,0}\left[\frac{\alpha\beta h}{A_0 h_l}\Bigg|_{-1+\xi^2,\ \alpha-1, \beta-1}^{\xi^2}\right] dh \tag{9}$$

By expressing the erfc($\cdot$) as Meijer G function [27, Eq. (8.4.14.2)], the probability of average BER can be expressed in a closed-form by utilizing [23, Eq. (21)]. As proved in Appendix B, this integration can be simplified to obtain

$$P_e = \frac{2^{\alpha+\beta-4}\xi^2}{\sqrt{\pi^3}\Gamma(\alpha)\Gamma(\beta)} G_{7,4}^{2,6}\left[\frac{4\gamma^2 A_0^2 h_l^2}{\sigma_n^2\alpha^2\beta^2}\Bigg|_{0, \frac{1}{2}, \frac{-\xi^2}{2}, \frac{-\xi^2+1}{2}}^{\frac{1-\xi^2}{2}, \frac{2-\xi^2}{2}, \frac{1-\alpha}{2}, \frac{2-\alpha}{2}, \frac{1-\beta}{2}, \frac{2-\beta}{2}, 1}\right] \tag{10}$$

4.2. Channel capacity

The channel capacity is a quantitative measurement of the limiting data transmission rate that can be achieved through a non-deterministic fading channel with a minimum probability of error. For a BPSK based SIM-FSO channel it can be estimated using