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Asymptotic bit error rate analysis of free space optical systems using spatial diversity

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ABSTRACT

Free space optical (FSO) communication is used to provide very high speed network connection to end users, especially the last mile users thereby enabling cost-effective, fast and secure internet service to them. But the single input single output (SISO) connection is highly hampered by the atmospheric turbulence and pointing error of the link. As a solution to this problem, the spatial diversity technique can be used to improve the communication service. The bit error rate (BER) analysis for the received signal to noise ratio (SNR) is analyzed in this paper to study the performance improvement over the SISO case for the system over the generalized atmospheric turbulence channel known as the Málaga turbulence channel. A new expression for the BER in terms of the beta function is derived and the diversity gain and coding gain are obtained from the same.

1. Introduction

Free space optical (FSO) communication technology is one of the fastest and inexpensive access provider technique for the next generation of wireless communication systems. A large number of users who are within a mile of the fiber backbone can be very easily connected within short time and low cost using the FSO communication systems. Along with the easy and cheap connectivity they also provide benefits such as high speed, reconfigurability, security from eavesdroppers and license free spectrum usage [1]. However, the single input single output (SISO) FSO system performance is very poor as the free space link is severely affected by the turbulence arising because of temperature and pressure variations of the channel. The link should also maintain proper line of sight (LOS) as the signal used belongs to the optical or near infra red (IR) spectrum. So any misalignment arising because of movement of the equipment due to various natural or man-made phenomena results in the signal outage [2–4].

In order to overcome the destructive effects of the channel turbulence and to improve the performance of FSO communication systems, the channel diversity techniques and relay techniques can be incorporated. In [5], the FSO performance improvement using the Amplify-Forward relay is analyzed. The other useful technique to improve the FSO communication performance is to make use of multiple transmit apertures and receive apertures. The multiple input multiple output (MIMO) architecture for FSO systems is studied in [6]. The diversity order analysis for communication systems in Gamma–Gamma channel is carried out by deriving outage probability and bit error rate (BER) in [7–9]. As per the existing literature, all the MIMO system analysis are done for different channel models which applies for weak, moderate or strong turbulence separately and there is a gap in analysis for a generic channel model such as the Málaga ($\mathcal{M}$) distribution [10]. Thus in this work, an FSO system with transmit and/or receive diversity schemes using maximal ratio combining (MRC) which is the most optimal diversity combining technique and equal gain combining (EGC) technique which is less complex and easy to implement at the receiver [7] are considered for analysis over the $\mathcal{M}$-distribution turbulence channel. $\mathcal{M}$-distribution model is a generalized channel model which encompasses the weak to strong fading and can be used to model the other major FSO channel models as well such as Gamma–Gamma, K-distribution , Log-Normal etc. [11] by proper substitution of values for the necessary parameters. The main contribution of this work is to derive and analyze the average BER expression and deduce the diversity gain and coding gain of the FSO system over the generalized channel model, $\mathcal{M}$-distribution. The final closed-form BER expression obtained is in terms of Beta function $B(x, y)$ [12, Eq. (8.380)] unlike the existing literature for FSO communication systems.

The rest of the contents of the paper includes the system and the channel models which are described in Section 2. Section 3 analyzes the asymptotic BER performance of the system and subsequently the

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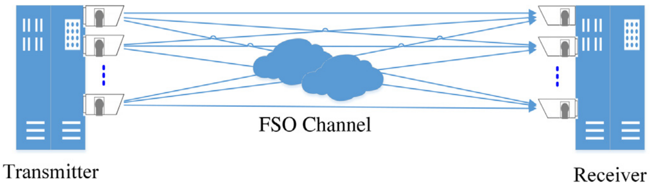

Fig. 1. FSO MIMO system model.

numerical results are presented in Section 4 and the conclusions are in Section 5.

2. System model

In the system considered, there is a transmit node equipped with M transmit apertures and a receive node with N receive apertures as shown in Fig. 1. The transmitter broadcasts the signal after modulating the information using Binary Phase Shift Keying Subcarrier intensity modulation (BPSK-SIM) scheme [4] and by repetition coding through its transmit apertures and the receiver combines the incoming signals using MRC or EGC technique [8]. If at any given instant, symbol x is transmitted, then the received symbol, y_n at the nth receive aperture can be expressed as,

$$y_n = \sum_{i=1}^{N} h_{n,m} x + n_n. \tag{1}$$

where $h_{n,m}$ is the channel coefficient and n_n is the additive white gaussian noise (AWGN) in the receiver which can be modeled by gaussian distribution.

2.1. Channel model

The combined channel model of atmospheric turbulence and misalignment fading can be modeled in the best manner using the $\mathcal{M}$-distribution function. It models the channel by dividing the transmitted beam into three components at the receiver, the LOS component U_L with average power of $\Omega = E[|U_L|^2]$, a scattered but coupled component to the LOS signal, U_S^C with an average power of $2\rho b_0$, and finally there is an independent scattered component U_S^G with average power of $2(1-\rho)b_0$. The parameter $\rho \le 1$ refers to the amount of coupling of the U_S^C component to U_L component. Therefore, the total power in the scattered components is $2\rho b_0$ and Ω' represents the average power of coherent contributions expressed as $\Omega' = \Omega + \rho 2b_0 + 2\sqrt{\rho 2 b_0 \Omega}\cos(\phi_A - \phi_B)$ [11]. Here, phases ϕ_A and ϕ_B belongs to components U_L and U_S^C respectively and are deterministic in nature. The elaborate channel description is present in [11]. The probability density function (PDF) of the channel coefficient $h_{n,m}$ following $\mathcal{M}$-distribution can be expressed as [3, Eq. (21)]

$$f_{h_{n,m}}(h_{n,m}) = \frac{g_{n,m}^2 A_{n,m}}{2h_{n,m}} \sum_{k=1}^{\beta_{n,m}} b_{k_{n,m}} G_{1,3}^{3,0}\left(B_{n,m} h_{n,m} \,\middle|\, \begin{matrix} g_{n,m}^2+1 \\ g_{n,m}^2, \alpha_{n,m}, k \end{matrix} \right) \tag{2}$$

where,

$$A_{n,m} = \frac{2\alpha_{n,m}^{\frac{\alpha_{n,m}}{2}}}{\xi_g^{1+\frac{\alpha_{n,m}}{2}} \Gamma(\alpha_{n,m})} \left(\frac{\xi_g \beta_{n,m}}{\xi_g \beta_{n,m} + \Omega'} \right)^{\beta_{n,m} + \frac{\alpha_{n,m}}{2}},$$

$$B_{n,m} = \frac{\alpha_{n,m}\beta_{n,m}}{(\xi_g \beta_{n,m} + \Omega') A_0},$$

$$b_{k_{n,m}} = a_{k_{n,m}} \left(\frac{\xi_g \beta_{n,m} + \Omega'}{\alpha_{n,m}\beta_{n,m}} \right)^{\frac{\alpha_{n,m}+k}{2}},$$

and

$$a_{k_{n,m}} = \binom{\beta_{n,m}-1}{k-1} \frac{(\xi_g \beta_{n,m} + \Omega')^{1-\frac{k}{2}}}{(k-1)!} \left(\frac{\Omega'}{\xi_g} \right)^{k-1} \left(\frac{\alpha_{n,m}}{\beta_{n,m}} \right)^{\frac{k}{2}}.$$

The parameter ξ_g is equal to $E[|U_S^G|^2] = (1-\rho)2b_0$, $\alpha_{n,m}$ is a positive number related to the effective number of large-scale scattering cells of the medium and $\beta_{n,m}$ is a natural number which represents how much scintillation is present in the transmitted signal [11]. The effect of pointing error is represented by $g_{n,m} = \frac{w_{zeq}}{\sigma_s}$, where w_{zeq} is the equivalent beam width such that $w_{zeq}^2 = w_z^2 \sqrt{\pi} erf(v)/2v \exp(-v^2)$ wherein $v = \sqrt{\pi} a_r / \sqrt{2} w_z$, a_r is radius of receive aperture and w_z is beamwidth. σ_s is the standard deviation of the pointing error displacement (jitter) at the receiver [3].

3. Error rate analysis

In this section the BER analysis for various combining schemes is carried out for the aforementioned FSO communication system.

3.1. Maximal ratio combining

If the transmitted optical power is represented as P_t, η represents the optical to electrical conversion coefficient of the receiver and σ^2 is the variance of the AWGN at the receiver, then the received SNR, γ after performing MRC of the received signals can be expressed as,

$$\gamma = \frac{(\eta P_t)^2}{M^2 N \sigma^2} \sum_{n=1}^{N} \left(\sum_{m=1}^{M} h_{n,m} \right)^2 = \frac{\bar{\gamma}}{N} \sum_{n=1}^{N} \left(\sum_{m=1}^{M} h_{n,m} \right)^2. \tag{3}$$

$\bar{\gamma}$ is the average received electrical SNR given as $\bar{\gamma} = \left(\frac{\eta P_t}{M\sigma}\right)^2$. At any instant, for a given channel coefficient, the BER for BPSK-SIM system can be expressed as $Q\left(\sqrt{\frac{\bar{\gamma}}{N}\sum_{n=1}^{N}\left(\sum_{m=1}^{M} h_{n,m}\right)^2}\right)$ [4]. Moreover, the Q-function can be expressed as [12]

$$Q(x) = \frac{1}{\pi} \int_0^{\pi/2} \exp\left(\frac{-x^2}{2\sin^2\theta} \right) d\theta. \tag{4}$$

Thus the instantaneous BER of the system will be

$$P_{ber}(i) = \frac{1}{\pi} \int_0^{\pi/2} \exp\left(\frac{-\frac{\bar{\gamma}}{N} \sum_{n=1}^{N} \left(\sum_{m=1}^{M} h_{n,m}\right)^2}{2\sin^2\theta} \right) d\theta$$
$$= \frac{1}{\pi} \int_0^{\pi/2} \prod_{n=1}^{N} \exp\left(\frac{-\frac{\bar{\gamma}}{N} \left(\sum_{m=1}^{M} h_{n,m}\right)^2}{2\sin^2\theta} \right) d\theta. \tag{5}$$

The average BER is $P_{ber} = E(P_{ber}(i))$ where E(.) stands for expectation operator and it can be expressed as

$$P_{ber} = \frac{1}{\pi} \int_0^{\infty} \left(\int_0^{\pi/2} \prod_{n=1}^{N} \exp\left(\frac{-\frac{\bar{\gamma}}{N} \left(\sum_{m=1}^{M} h_{n,m}\right)^2}{2\sin^2\theta} \right) d\theta \right) f_h(h) dh \tag{6}$$

The integral in Eq. (6) cannot be solved analytically but only numerically. Thus for simplicity the special case of receiver diversity alone (single input multiple output, SIMO) is considered assuming N receive apertures and only a single transmit aperture ($M = 1$). Also by assuming that all the links are independent, the overall channel PDF can be expressed as $f_h(h) = \prod_{n=1}^{N} f_{h_n}(h_n)$. Thus, by substituting the overall channel PDF in (6) after rearranging the integrals, the average BER performance can be expressed as,

$$P_{ber} = \frac{1}{\pi} \prod_{n=1}^{N} \int_0^{\pi/2} \int_0^{\infty} \exp\left(\frac{-\bar{\gamma} h_n{}^2}{N \sin^2\theta} \right) f_{h_n}(h_n) dh_n d\theta \tag{7}$$