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Coherent Binary Polarization Shift Keying in Free Space Optical Turbulence Channel

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Abstract—In this paper the performance of a binary polarization shift keying (BPOLSK) modulated free space optical (FSO) link employing coherent detection in the presence of the atmospheric turbulence is investigated. First, a closed-form expression for the bit error rate (BER) of a BPOLSK-FSO system is presented taking into account the atmospheric turbulence-induced fading and noise. The BER performance of BPOLSK and on-off keying (OOK) with fixed and adaptive threshold schemes in the atmospheric turbulence channel is also shown.

Index Terms—FSO, coherent detection, polarization modulation, BER and outage probability.

I. INTRODUCTION

The FSO technology has attracted much attention as a means to deal with the rise in bandwidth demand in core networks and multi-user access systems [1]. It is best suited for the point-to-point, high-capacity (multi-Gb/s) links spanning up to a few kilometers – in “last-mile” access network applications. However, FSO links are sensitive to atmospheric turbulence which is caused due to the air temperature inhomogeneities [2]. Light signal propagating through the turbulence channel will experience random fluctuation of phase and amplitude, which is referred to as the scintillation. It causes received power degradation, thus significantly limiting the transmission speed and the link range. Various models describing the probability density function (PDF) of the irradiance fluctuation have been developed. Lognormal distribution is the simplest turbulence model valid only for weak turbulence regime and is derived based on Rytov approximation [3]. Beyond the weak regime, where multiple scatterings exist, Rytov approximation is no longer valid [4, 5]. Therefore, the gamma-gamma and negative exponential models corresponding to the weak-to-strong and saturation regimes, respectively, have been widely used [6, 7].

Several approaches have been proposed to circumvent the atmospheric turbulence [8-10]. However, for optical beams propagating through a turbulent channel, the states of polarization are the most stable properties compared to the amplitude, phase and frequency, which can be maintained over a long propagation link [11, 12]. In this work we analyze BPOLSK with the coherent heterodyne detection for the FSO link under the atmosphere turbulence. Through

comparison with OOK, the performance advantage of the BPOLSK-FSO system is outlined. The performance analysis will be based on the lognormal and negative exponential channel models. Since the FSO link under consideration is LOS, the ISI due to the multipath propagation is not considered here. The noise (the background radiation, thermal noise and shot noise) is modeled as an additive white Gaussian noise (AWGN) process.

The rest of the paper is organized as follows: the BPOLSK-FSO system structure is showed in Section II. The BER of BPOLSK system under the atmospheric turbulence channel has been analyzed in Section III. The results discussion is in Section IV. Finally, the conclusion is presented in Section V.

II. BPOLSK-FSO SYSTEM

The system configuration of BPOLSK-FSO using the coherent detection is shown in Fig. 1. The optical carrier $\vec{E}_0(t)$ from a laser source is linearly polarized along $\pi/4$ with respect to the reference axis of the PBS. $\vec{E}_0(t)$ is split equally into two equal components – \vec{x} and \vec{y} polarizations. Only the \vec{x} -component is phase-modulated between 0 and π depending on the input data stream, which leads to either $\pi/4$ or $3\pi/4$ polarization state of the optical carrier, respectively. The transmitted optical signal $\vec{E}_s(t)$ is expressed as:

$$\vec{E}_s(t) = \sqrt{0.5P_t} e^{i(\omega t + \varphi(t))} \{e^{i\beta_x(t)} \cdot \vec{x} + \vec{y}\}, \quad (1)$$

where P_t , ω , and $\varphi(t)$ are the power, the angular frequency and the phase noise of the optical carrier, respectively. $\beta_x(t) = [0, \pi]$ is the phase difference between the two field components \vec{x} and \vec{y} .

At the receiver an optical bandpass filter (OBPF) with a well defined field of view and bandwidth of ~ 1 nm is located at the front end in order to reduce the impact of the background light interference. The bandwidth of OBPF depends on the linewidth (LW) of the laser source, which has a narrow LW typically < 1 nm. The received signal $\vec{E}_r(t)$ can be viewed in both cases as two orthogonal amplitude modulated signals, related to the orthogonal components of $\vec{E}_s(t)$. The local oscillator (LO) laser linearly polarized at $\pi/4$ is identical to the transmitter laser. The AFC module, of which the control signal derived from the IF signal, is a

closed-loop circuit acting on the bias current. Its working principle is for system synchronisation and for compensating the slow-frequency fluctuations in LO [13]. The received optical signal $\vec{E}_r(t)$ and the LO signal $\vec{E}_{lo}(t)$ are given as:

$$\vec{E}_r(t) = \sqrt{0.5P_r} e^{i(\omega t + \varphi_r(t))} \{e^{i\beta_x(t)} \cdot \vec{x} + \vec{y}\}. \quad (2)$$

$$\vec{E}_{lo}(t) = 0.5\sqrt{P_{lo}} e^{i(\omega_{lo}t + \varphi_{lo}(t))} \{\vec{x} + \vec{y}\}. \quad (3)$$

Both P_r and $\varphi_r(t)$ are time-variant quantities due to the turbulence fluctuation. P_{lo} , ω_{lo} and $\varphi_{lo}(t)$ represent the power, angular frequency and the phase noise of the LO, respectively. $\vec{E}_r(t)$ is split by the PBS and mixed with the corresponding components of $\vec{E}_{lo}(t)$ before being applied to two identical PDs with a unit area. PDs outputs are passed through ideal electric BPFs with a bandwidth and a center frequency of $B_{bp} = 2(Rs + k_f B_L)$ and ω_{IF} , respectively. R_s and B_L are the symbol rate and LW of laser sources, respectively. It is assumed that BPFs are ideal which only pass the signal without any distortion, thus the filter outputs are expressed by:

$$c_{xb}(t) = \Re\sqrt{P_r P_{lo}/2} \cos(\omega_{IF}t + \beta_x(t) + \varphi_{IF}(t)) + n_x(t), \quad (4a)$$

$$c_{yb}(t) = \Re\sqrt{P_r P_{lo}/2} \cos(\omega_{IF}t + \varphi_{IF}(t)) + n_y(t). \quad (4b)$$

where \Re is the photodiode responsivity, $\omega_{IF} = \omega - \omega_{lo}$ and $\varphi_{IF}(t) = \varphi_r(t) - \varphi_{lo}(t)$ are the frequency and phase noise of the intermediate signal (IF), respectively. The noise terms $n_{x,y}(t) \sim N(0, \sigma_n^2)$ are assumed to be statistically independent AWGN with variance σ_n^2 comprising of the thermal noise (σ_T^2) and the background radiation shot noise (σ_B^2), i.e., $\sigma_n^2 = \sigma_T^2 + \sigma_B^2$. Both noise terms are uncorrelated such that $n_x(t) \cdot n_y(t) = 0$. The noise signals $n_{x,y}(t)$ in (4) can be expressed as [14, 15]:

$$n(t) = n^I(t)\cos(\omega_{IF}t + \varphi_{IF}(t)) - n^Q(t)\sin(\omega_{IF}t + \varphi_{IF}(t)), \quad (5)$$

where $n^I(t)$ and $n^Q(t)$ are the in-phase and quadrature components of the noise $n(t) \sim N(0, \sigma_n^2)$, respectively. The electric currents $c_{xb}(t)$ and $c_{yb}(t)$ are processed by the mixer to generate $c(t)$, which is then fed into the matched

filter (MF). The output of the MF is passed through a sampler and a threshold detector.

The output of the MF V_j is passed through a sampler and a threshold detector. A binary '0' is assumed to be received if V_j is above the threshold level of zero and '1' otherwise. Assuming independent and identically distributed (i.i.d.) data transmission, the electric signal V_j is expressed as:

$$V_j = 0.5z\sqrt{0.5\Re^2 P_r P_{lo}} \quad (6)$$

where $z = \sqrt{0.5\Re^2 P_r P_{lo}} + n_x^I(t) + n_y^I(t)$ whose PDF is $f(z)$ and denoted as $z \sim N(0.5\Re^2 P_r P_{lo}, \sigma_n^2)$. Under the assumption of ideal channel, the conditional BER P_{ec} is derived as:

$$P_{ec} = Q\left(\sqrt{\Re^2 P_r P_{lo}/2\sigma_n^2}\right) = Q(\sqrt{\gamma}) \quad (7)$$

where the electrical SNR per bit is given by $\gamma = \Re^2 P_r P_{lo}/2\sigma_n^2$.

III. LINK PERFORMANCE OF BPOLSK-FSO

Adopting the approach given in [16], the unconditional probabilities P_e in the weak and saturation regime are obtained by averaging (7) over the lognormal and negative exponential distribution PDFs:

$$P_{eLOG} = \int_0^\infty \frac{Q(\sqrt{\gamma(P_r)})}{P_r \sqrt{2\pi\sigma_l}} \exp\left\{-\frac{[\ln(P_r/P_0) + 0.5\sigma_l^2]^2}{2\sigma_l^2}\right\} dP_r. \quad (8)$$

$$P_{eNEG} = \int_0^\infty Q(\sqrt{\gamma(P_r)}) \frac{1}{P_0} \exp\left(-\frac{P_r}{P_0}\right) dP_r. \quad (9)$$

No closed form solutions for (8) and (9) exist that could result in truncating its upper limit by using the numerical integration. Furthermore, the presence of the argument of the Q-function always causes analytical problems at the lower limit of the Q-function integral [17]. By combining an alternative form of the Q-function with the Gauss-Hermite quadrature integration approximation [16], the analytical difficulty in solving (8) and (9) can be overcome. By invoking variable change as $y = [\ln(P_r/P_0) + 0.5\sigma_l^2]/\sqrt{2}\sigma_l$ in (8), the unconditional BER can be reduced to the following form:

$$P_{eLOG} = \frac{1}{\sqrt{\pi}} \sum_{i=1}^n w_i Q\left(\sqrt{\Re^2 P_{lo}/2\sigma_n^2} P_0 \exp(\sqrt{2}\sigma_l x_i - 0.5\sigma_l^2)\right). \quad (10)$$

where $[w_i]_{i=1}^n$ and $[x_i]_{i=1}^n$ are the weight factors and the zeros of an n^{th} order Hermite polynomial, $He_n(x)$ [18]. The degree of accuracy of (10) depends on the order n of $He_n(x)$. By using the alternative representation of $Q(\cdot)$, the unconditional BER in the saturation regime and beyond is derived by averaging the conditional BER over the fully developed speckle PDF:

$$P_{eNEG} = \frac{1}{\pi P_0} \int_0^{\pi/2} \int_0^\infty \exp\left(-\frac{\Re^2 P_r P_{lo}}{4\sigma_n^2 \sin^2(\theta)} - \frac{P_r}{P_0}\right) dP_r d\theta. \quad (11)$$

Equation 3.322.2 in [19] is used to solve the multiple integration involved in (11). The BER is thus reduced to the following form:

$$P_{eNEG} = \frac{2}{\pi} \int_0^{\pi/2} \sqrt{\pi \mathcal{K}_0(\theta)} \exp(\mathcal{K}_0(\theta)) Q(\sqrt{2\mathcal{K}_0(\theta)}) d\theta. \quad (12)$$

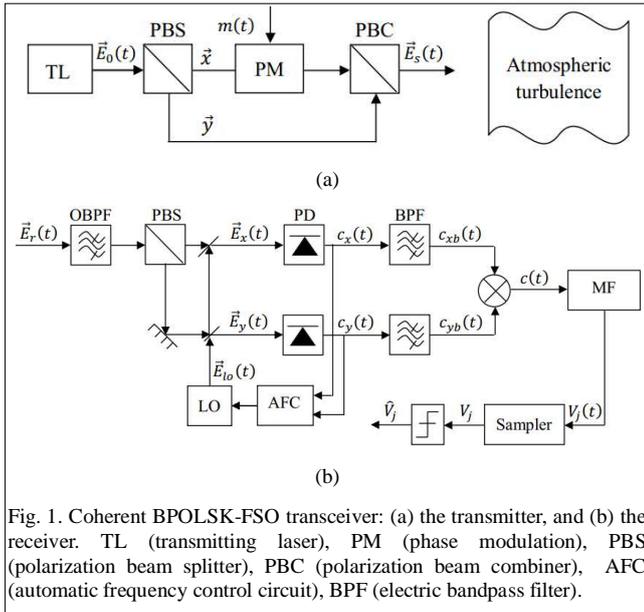


Fig. 1. Coherent BPOLSK-FSO transceiver: (a) the transmitter, and (b) the receiver. TL (transmitting laser), PM (phase modulation), PBS (polarization beam splitter), PBC (polarization beam combiner), AFC (automatic frequency control circuit), BPF (electric bandpass filter).

where $\mathcal{K}_0(\theta) = \sigma_n^2 \sin^2(\theta) / \mathcal{R}^2 P_{lo}$. The integral in (12) can be minimized with the substitution of $\theta = \pi/2$ in its integrant, leading to the upper bound below

$$P_{eNEG} \leq \sqrt{\pi \mathcal{K}_0} \exp(\mathcal{K}_0) Q(\sqrt{2\mathcal{K}_0}). \quad (13)$$

where $\mathcal{K}_0 = \sigma_n^2 / \mathcal{R}^2 P_{lo}$.

IV. RESULTS DISCUSSION

Figure 2 depicts the error probability against the normalized electrical SNR for BPOLSK and OOK with fixed and adaptive threshold schemes in the atmospheric turbulence channel. To achieve a BER of 10^{-9} , the SNR requirements for BPOLSK is ~ 3 dB more than OOK with no turbulence. To achieve a fixed BER, the SNR requirement increases with the turbulence level irrespective of the modulation schemes and it is higher for lower values of BER at the same turbulence level. For example, to achieve a BER of 10^{-9} at $\sigma_l^2 = 0.1$ in a weak turbulence regime, the SNR requirements for BPOLSK and OOK with adaptive threshold detection are ~ 24.5 dB and ~ 33.5 dB, respectively. When the BER increases to 10^{-6} , the corresponding SNR values drop to ~ 20 dB and ~ 28.5 dB, respectively. OOK with a fixed threshold suffers higher BER floor levels in the turbulence channel.

V. CONCLUSION

The performance of coherent BPOLSK-FSO system in the presence of atmospheric turbulence has been investigated. The closed-form expression for the unconditional BER of the BPOLSK-FSO operating in weak and saturation turbulence channels have also been presented. BER of BPOLSK and OOK with fixed and adaptive threshold schemes in the atmospheric turbulence channel has been shown. For example, to achieve a BER of 10^{-9} at $\sigma_l^2 = 0.1$ in a weak turbulence regime, SNR requirements for BPOLSK and OOK with the adaptive threshold detection are ~ 24.5 dB and

~ 33.5 dB, respectively. OOK with a fixed thresholding scheme suffers a higher BER floor levels in the turbulence channel.

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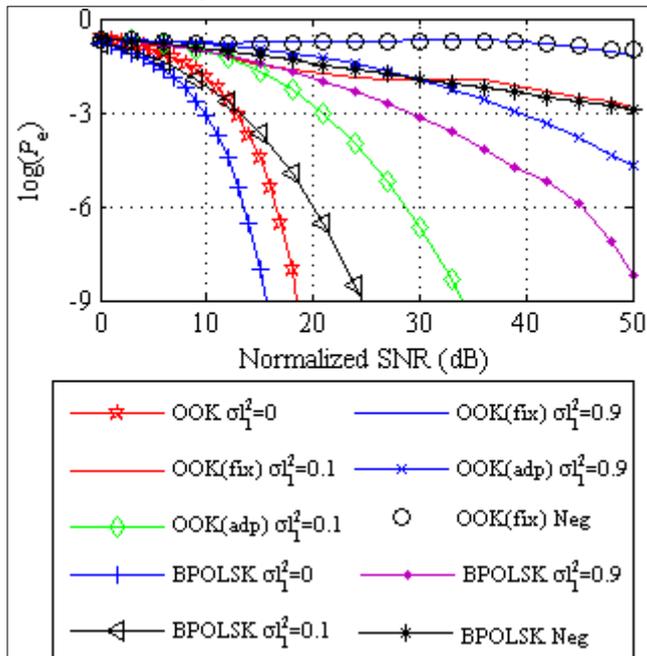


Fig. 2: Comparisons of BER performances of BPOLSK and OOK schemes against the normalized electric SNR $E[\mathcal{R}_r P_{lo}] = 1$ in the presence of turbulence.