Performance Analysis of FSO System with Different Modulation Schemes over Gamma-Gamma Turbulence Channel

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ABSTRACT

Free-space optical communications (FSO) suffers from irradiance fluctuation caused by atmospheric turbulence, which results in optical power loss and consequently decreased signal-to-noise ratio (SNR). The error performances of the FSO based on On-Off Keying (OOK), Differential Phase Shift Keying (DPSK), and Binary Phase Shift Keying (BPSK) schemes in a turbulent atmosphere are presented. The received irradiance after propagating the atmosphere is modeled using the gamma-gamma distribution to evaluate the system error performance in turbulence regimes from weak to strong. The results show that, to obtain a BER of 10^{-6} at weak turbulence regime, ~15 dB and ~18 dB SNRs are required for BPSK and DPSK, respectively. However, for OOK with a fixed threshold of 0.5 under the same channel condition, OOK reaches an error floor greater than 10^{-3}. The values of SNR required to achieve the same BER increase as the turbulence strength increase to moderate and strong regimes.

Keywords: Gamma-Gamma channel, OOK, BPSK, DPSK, free space optical, atmospheric turbulence

1. INTRODUCTION

Free space optical communications (FSO) is a bright technology offering a huge license-free frequency spectrum, immunity to electromagnetic interference, high security and low cost[1]. FSO link is based on transmitting information-bearing laser beam traverse the atmosphere and receiving the optical light by a telescope. The optical power of the laser beam passing through the atmosphere can be attenuated, absorbed or scattered by the atmospheric condition, which ultimately degrades the performances of FSO systems. FSO is less affected by snow and rain compared with the RF system, but can be severely affected by the atmospheric turbulence and fog.

Several kilometers of FSO link is easily achievable with a typical attenuation coefficient of 0.43 dB/km. For FSO with a link range over 1 km in clear atmosphere, the performances suffer from the effects of turbulence induced irradiance fluctuation[2, 3]. The irradiance fluctuation, also known as scintillation, is caused by atmospheric temperature and pressure inhomogeneity, which results in random fluctuations in both amplitude and phase of the optical signal[4].

Several typical of turbulence models have been proposed to study FSO performance under a clear atmospheric condition. Log normal turbulence model is widely reported and mathematically tractable. Log normal model is originally generated using the Rytov approximation, which of the precondition is the magnitude of the scattered field wave to be small compared to the unperturbed phase gradient. This assumption is only valid in single scattering event for weak turbulence while it becomes invalid for multiple scatterings in longer link ranges[5].

Atmospheric turbulence ultimately leads to deep signal fades lasts for~1-100 μs, which results in loss of up to 10^5 consecutive bits for a FSO link with the data rate of 1 Gbps[3][6]. The gamma-gamma turbulence model proposed by Andrews et al.[7] is based on the assumption that light radiation traversing turbulent atmosphere includes small scale (scattering) and large scale (refraction) effects and both effects follow the gamma distribution. The gamma-gamma model for the probability density function (pdf) of irradiance fluctuation is valid for all turbulence conditions from weak to strong.

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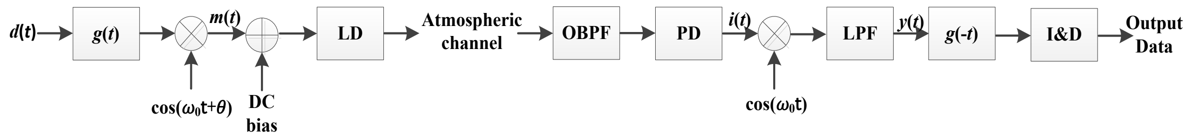
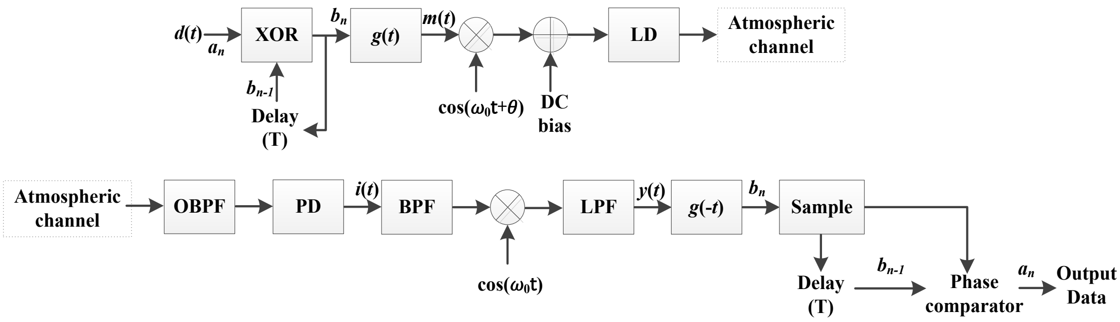
Intensity modulated FSO link is widely used in practical work but it mainly suffers from atmospheric turbulence, such as on-off keying (OOK) requires adaptive threshold to perform optimally in turbulence condition[8]. In this work binary phase shift keying (BPSK) and differential phase shift keying (DPSK) pre-modulated FSO links have been presented as well as OOK for performances comparisons. Gamma-gamma distribution is applied to modulate the atmospheric turbulence across weak to strong regime[9]. The additive white Gaussian noise (AWGN) is mainly composed of background radiation and the thermal noise. The remainder of the paper is organized as follows. Section II proposes OOK, BPSK and DPSK based FSO systems. Sections III and IV give the bit-error rate (BER) performance metric and the conclusion, respectively.

2. SYSTEM AND CHANNEL MODEL

2.1 System model



(a)



(b)

Fig 1. Block diagrams of: (a) BPSK-FSO, and (b) DPSK-FSO. (LD: laser driver, OBPF: optical band pass filter, PD: photo-detector, LPF: low pass filter, I&D: integration and dump.)

The block diagrams of BPSK and DPSK modulation schemes based FSO systems are shown in Fig. 1 (a) and 1(b), respectively. For the BPSK modulation, the '0' and '1' of data symbols are represented by two different phases 0 and π, respectively. The modulated signal $m(t)$ is obtained by multiplying the rectangular pulse shaping function $g(t)$ by the carrier signal, which is written as:

$$m(t) = A \times g(t)\cos(\omega_0 t + \theta) \tag{1}$$

where the ω_0 and θ represent the subcarrier angular frequency and phase respectively. A DC bias is added to $m(t)$ in order to ensure the intensity of output optical signal always be positive and then the signal is used to directly drive the laser. Then the photocurrent $i(t)$ is multiplied by the subcarrier signal, the output of which is passed through a low pass filter (LPF). Note that the signal with an angular frequency of $2\omega_0$ is filtered out. Therefore, the signal $i(t)$ is given as:

$$i(t) = \Re I \xi m(t) + n(t) \tag{2}$$

where ξ represents the optical modulation index, $\Re$ is the responsivity of PD, I represents the received optical power, and $n(t) \sim N(0, \sigma_n^2)$ is the AWGN.

Then the photocurrent $i(t)$ is multiplied by the subcarrier signal, the output of which is passed through a low pass filter (LPF). Note that the signal with an angular frequency of $2\omega_0$ is filtered out. Therefore, the signal $y(t)$ is given as:

$$y(t) = \frac{\Re I \xi A \times g(t)}{2} + \frac{n_I(t)}{2} \tag{3}$$

Finally the signal $y(t)$ is fed into the decision circuit.

The block diagram of DPSK is similar with that of BPSK. At the transmitter, it uses the phase difference of adjacent symbols to represent digital information. The phase changes only when symbol '1' is transmitted. The generated bits before pulse shaping are given by:

$$b_n = a_n \oplus b_{n-1} \tag{4}$$

The Demodulation of the DPSK signal is performed by comparing the phases of adjacent symbols, which is given by:

$$a_n = b_n \oplus b_{n-1} \tag{5}$$

2.2 BER characteristic using different modulation schemes

The expressions of the conditional probability BER of BPSK and DPSK are derived as the following Eqs. (6), (7) respectively[10]:

$$P_{ec,BPSK} = 0.5erfc\left(\sqrt{SNR}\right) \tag{6}$$

$$P_{ec,DPSK} = 0.5erfc\left(\frac{\sqrt{SNR}}{\sqrt{2}}\right) \tag{7}$$

For OOK modulation, the probability of conditional BER in atmospheric channel can be expressed by the follow Eq. (8):

$$P_{ec,ook}(i) = \int_0^{i_{th}} \frac{1}{\sqrt{2\pi\sigma_n^{\ 2}}} \exp\left[\frac{-(i-\Re I)^2}{2\sigma_n^2}\right] di + \int_{i_{th}}^{\infty} \frac{1}{\sqrt{2\pi\sigma_n^{\ 2}}} \exp\left(-i^2/2\sigma_n^{\ 2}\right) di \tag{8}$$

where i_{th} represents the threshold signal level and the adaptive threshold Λ is defined as (9), i is the average photocurrent.

$$\Lambda = \int_0^{\infty} \exp\left[\frac{-(i-\Re I)^2 - i^2}{2\sigma_n^2}\right] P(I)\, dI \tag{9}$$

The GG model for the PDF of irradiance fluctuation $P(I)$ can be given as (10):

$$p(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\left(\frac{\alpha+\beta}{2}\right)-1} \mathrm{K}_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \tag{10}$$

where α and β represent the values of effective number of large and small scale eddies, respectively. $\Gamma(.)$ represents the gamma function, and $K_n(.)$ is the nth modified Bessel function. For plane waves, the expression of α and β are given by:

$$\alpha = \left[\exp\left(\frac{0.49\sigma_l^{\ 2}}{\left(1+1.11\sigma_l^{\ 12/5}\right)^{7/6}} - 1\right)\right]^{-1} \tag{11}$$

$$\beta = \left[\exp\left(\frac{0.51\sigma_l^{\ 2}}{\left(1+0.69\sigma_l^{\ 12/5}\right)^{5/6}} - 1\right)\right]^{-1} \tag{12}$$

where σ_l^2 represents the turbulence strength.

The probability of unconditional BER based FSO systems under GG turbulence channel is defined as Eq. (13).

$$P_e(I) = \int_0^{\infty} P_{ec,M}(I) P(I)\, dI \tag{13}$$

where $P_{ec,M}$ represents the probability of conditional BER for BPSK, DPSK and OOK.

3. NUMERICAL RESULTS AND ANALYSIS

In this section, the numerical results can be derived based on the analytical expressions in section 2. As shown in Table 1, the values of parameters α and β represent the turbulence strength. As shown in Figs. 2–4, the BER against signal to noise rate (SNR) for OOK (fixed (i_{th}=0.5) and adaptive thresholds), BPSK and DPSK are calculated and plotted. The fixed and adaptive thresholds are used in OOK modulation. Note that the adaptive threshold is used to improve the BER performance of the OOK-FSO system. It shows that the required SNR to achieve the same BER increases as the turbulence strength increased for all the modulation techniques. For example, to obtain a BER of 10^{-6} using DPSK modulation technique, 18 dB and 34 dB SNRs are required for a very weak turbulence strength (σ_l^2=0.2) and a moderate turbulence strength (σ_l^2=1.4), respectively. To obtain a BER of 10^{-6} at the fading strength σ_l^2 of 3, 36 dB and 33 dB SNRs are required for DPSK and BPSK, respectively. In case of DPSK modulation, 3dB more power is required in order to obtain the same BER as compared to BPSK modulation under the same fading strength.

Based on the above expressions, the SNR penalties of DPSK and BPSK modulation schemes with different turbulence strength are plotted in Figs. 5 and 6, respectively. The SNR penalty is defined as the difference between the required SNRs to obtain a given BER in the presence and absence of atmospheric turbulence. The SNR penalties for DPSK and BPSK at the BER of 10^{-2}, 10^{-4} and 10^{-6} are shown in Figs. 5 and 6, respectively. For example, when the fading strength σ_l^2 increases from 0.1 to 0.3, the penalty rises from 5 dB to 8 dB at a BER of 10^{-4} for DPSK while the penalty to obtain the same BER for BPSK increases from 4 dB to 7 dB in the same turbulence condition. To obtain a BER of 10^{-6} as the fading strength increases to 3.5, the SNR penalties are 26 dB and 24 dB for DPSK and BPSK, respectively.

Table 1: Fading strength of different turbulence regimes for GG channel.

Parameter	Turbulence Condition		
	Weak	Moderate	Strong
σ_l^2	0.2	1.4	3
α	11.65	4.08	4.12
β	10.12	2.06	1.44

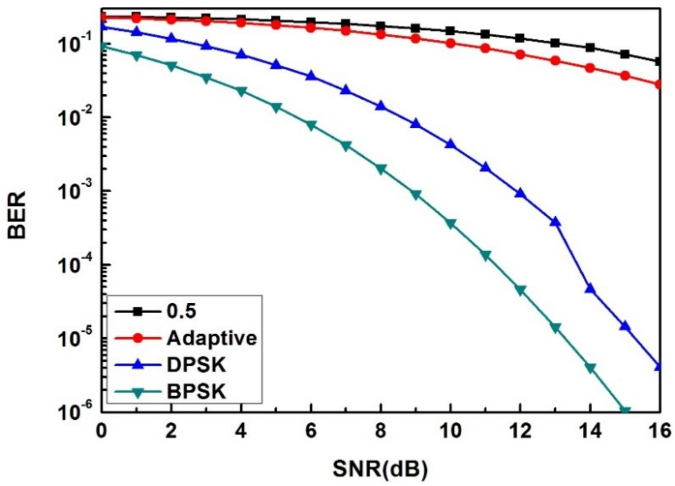


Fig 2. BER against SNR for OOK (a fixed threshold of 0.5 and adaptive threshold), DPSK and BPSK with α = 11.65, β = 10.12.

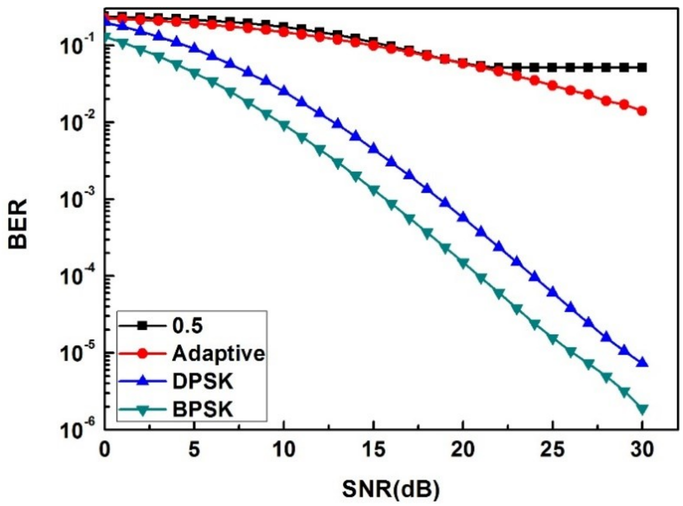


Fig 3. BER against SNR for OOK (a fixed threshold of 0.5 and adaptive threshold), DPSK and BPSK with $\alpha = 4.08$, $\beta = 2.06$.

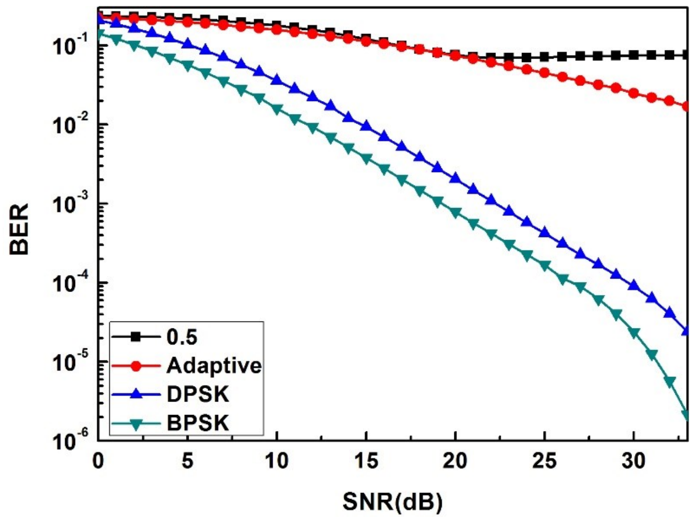


Fig 4. BER against SNR for OOK (a fixed threshold of 0.5 and adaptive threshold), DPSK and BPSK with $\alpha = 4.12$, $\beta = 1.44$.

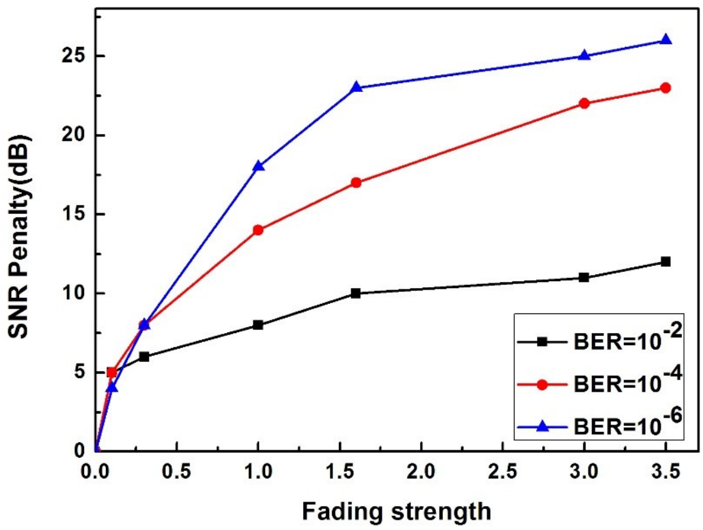


Fig 5. Turbulence induced SNR penalty as function of fading strength for DPSK based FSO.

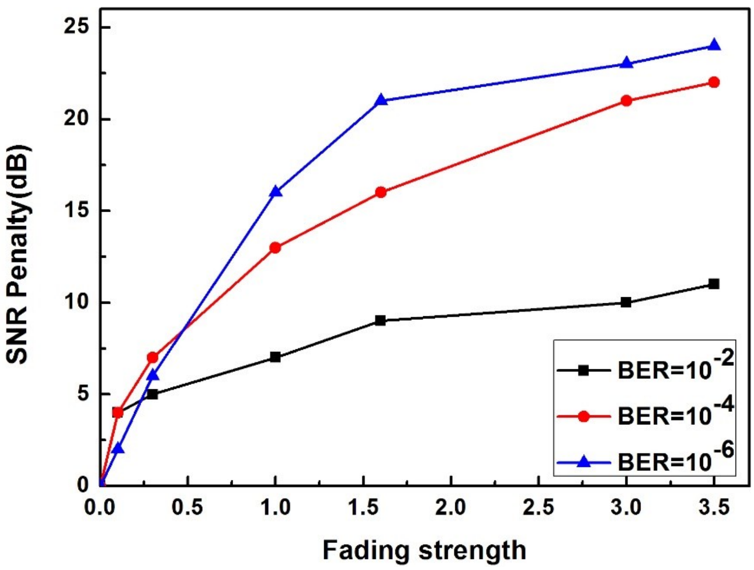


Fig 6. Turbulence induced SNR penalty as function of fading strength for BPSK based FSO.

4. CONCLUSION

In this work, various modulation schemes used in FSO systems were studied. The BER expressions for the BPSK, OOK and DPSK modulations were derived. The results showed that BPSK was a better modulation technique for FSO due to its better BER performance under the atmospheric turbulence compared to DPSK and OOK. The OOK modulation required adaptive threshold to perform optimally in the turbulence condition. To obtain a BER of 10^{-6} at weak turbulence regime, ~15 dB and ~18 dB SNRs were required for BPSK and DPSK, respectively. However, for OOK with a fixed threshold of 0.5 under the same channel condition, OOK reached an error floor greater than 10^{-3}. The values of SNR required to achieve the same BER increased as the turbulence strength increased to moderate and strong regimes.

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