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EFFECT OF PHASE NOISE ON BIT ERROR RATE PERFORMANCE OF BPSK SUBCARRIER INTENSITY MODULATED WIRELESS OPTICAL SYSTEMS – SIMULATION STUDY*

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Abstract. *In this paper, the bit error rate (BER) performance of binary phase-shift keying (BPSK)-based subcarrier intensity modulated (SIM) free space optical (FSO) communication system is analyzed. The influence of imperfect reference signal recovery on BER values in detecting PSK SIM signals transmitted over Gamma-Gamma turbulence channel was determined by Monte Carlo simulations. Simulations results indicate that imperfect reference signal recovery causes the irreducible error floor that is an important system characteristic.*

Key words: *bit error rate, free space optics, modulations, Monte Carlo simulations, phase-locked loop*

1. INTRODUCTION

Wireless optical (WO) communications, also known as free space optical (FSO) communications, have received considerable attention among both research and industrial community during the last decade. The FSO can be utilized for very short-range optical interconnects on integrated circuit, indoor applications, outdoor connections between buildings, as well as ground-to-satellite, aircraft-to-satellite and satellite-to-satellite links. The FSO systems are especially applied for last-mile connectivity, connectivity between

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local area networks and extension of the existing metropolitan area networks rings. The FSO systems have some advantages compared with RF systems. Some of them are unregulated spectrum bandwidth, lower power consumption, immunity to electromagnetic interference, higher data rate, quick deployment, etc. Typical wavelengths used in terrestrial outdoor FSO systems are 850 and 1550 nm. Depending on weather conditions and taking into account regulations relating to eye safety, the length of FSO links is from several hundred meters to several kilometers. Some commercial systems operate with data rates greater than 1 Gbps over distances up to 5 km offering different services as transmission of data, voice and video signals [1], [2].

Optical wave propagation in FSO systems is influenced by absorption, scattering and refractive-index fluctuations. Absorption and scattering can be taken into account through attenuation, while optical turbulence causes irradiance fluctuations of the transmitted optical signal. These fluctuations can be described by several statistical distributions. The recently proposed Gamma-Gamma probability density function (PDF) is very general and can describe accurately both weak and deep turbulence fluctuations [2].

Modulation techniques applied in FSO systems can be divided into two groups: intensity-modulation direct-detection (IM/DD) formats and coherent detection formats. In IM/DD systems the transmitted information is associated with the intensity variation of the transmitted optical signal and is directly demodulated at the receiver. The disadvantage of this technique is non-constant detection threshold depending on channel conditions. In coherent detection the optical signal is modulated by information bits by changing amplitude, phase or frequency of the lightwave. The receiver contains local oscillator to down convert the carrier to baseband or intermediate frequency carrier. The practical realization of optical and electrical part of the receiver can be complex. The subcarrier intensity modulation (SIM) has been recently proposed for applications in FSO systems [3]. The SIM was initially applied in multiple carrier RF communications for 4G mobile systems, optical fiber communications, asymmetric digital subcarrier lines, etc. By applying this technique, the phase-shift keyed (PSK) RF signal is directly transmitted over IM/DD FSO system. These SIM FSO systems have better BER performance compared with pure IM/DD systems and do not require local oscillator at the receiver as coherent detection-based FSO systems.

The BER performance of these PSK-based SIM systems has been determined in [3]-[6]. The starting assumption in these papers was perfect reference signal extraction at the receiver after optical-to-electrical conversion. From practical point of view it is very hard to perfectly estimate the phase of the received signal. This effect of imperfect reference signal extraction was analyzed in [7] for FSO systems based on coherent detection, but has not been considered in SIM FSO systems. The aim of this paper is to analyze the effect of this imperfect reference signal recovery on BER performance of binary PSK (BPSK) pre-modulated SIM-based FSO systems. By means of Monte Carlo simulations [8], we determine BER performance for different values of average electrical signal-to-noise ratio, turbulence parameters and standard deviation of phase noise. The phase noise is difference between phases of received signal and extracted reference signal. This phase noise is a stochastic process that can be described by Tikhonov distribution [7].

The paper is organized as follows. Section 2 presents system, channel and simulation model. The simulations results with appropriate comments are given in Section 3, while Section 4 offers some concluding remarks.

2. SYSTEM AND CHANNEL MODEL

In this Section, the modulation and demodulation processes are presented, and after that the channel and simulation models are briefly described.

2.1. System model

Let us consider a SIM FSO system presented in Fig. 1. The information data is first used for modulating an RF subcarrier using BPSK. The modulated subcarrier signal can be presented as

$$m(t) = \sum_k g(t - kT)\cos(\omega_c t + \phi_k)\,, \tag{1}$$

where $g(t)$ is a rectangular shaping pulse, T is a bit duration, ω_c is a carrier angular frequency, and ϕ_k is equal to 0 or π depending on a binary one or a binary zero is transmitted. The modulated signal $m(t)$ is DC-level shifted to ensure that bias current is grater than or equal to the specified threshold current. After that, the laser irradiance is modulated by DC-level shifted modulated subcarrier. The transmitted optical power is given by

$$P_t(t) = P(1 + \mu m(t))\,, \tag{2}$$

where P is the average transmitted optical power, and μ ($0<\mu<1$) denotes the modulation index. After that the optical signal is transmitted over a wireless channel exhibiting turbulence effects. The irradiance of the received optical signal is a stochastic process denoted by $I(t)$.The received optical signal is detected by PIN photodiode, with receiver optical-to-electrical efficiency denoted by R, which is followed by electrical band-pass filter with centre frequency ω_c. This filter removes the DC component and allows the SIM signal to pass through it. The received electrical signal at the receiver can be presented as

$$i_e(t) = \pm RIg(t)\cos(\omega_c t + \theta(t)) + n(t)\,, \tag{3}$$

where $n(t)$ is the channel noise that has Gaussian distribution with zero mean value and standard deviation denoted by σ. The electrical signal-to-noise ratio (SNR) at the demodulator input is defined as

$$\gamma = \frac{(IR)^2}{2\sigma^2} \tag{4}$$

and average electrical SNR is defined by

$$\gamma_{sr} = \frac{(\mathrm{E[I]}R)^2}{2\sigma^2}\,, \tag{5}$$

where E[.] denotes expectation operator.

The electrical signal $i_e(t)$ is multiplied by reference signal $2\cos(\omega_c t + \hat{\theta}(t))$ extracted by phase-locked loop (PLL). The signal that is sampled has the form

$$i_{ei}(t) = \pm RI(t)\cos\varphi(t) + x(t)\,, \tag{6}$$

where $\varphi(t)$ is the difference between the electrical signal phase and extracted reference signal phase, $\varphi(t) = \theta(t) - \hat{\theta}(t)$. This difference is a stochastic process with Tikhonov PDF given by [7]

$$p_\varphi(\varphi) = \frac{1}{2\pi} \frac{e^{\alpha \cos\varphi}}{I_0(\alpha)}, \ -\pi < \varphi \le \pi \ , \tag{7}$$

where $\alpha = 1 / \sigma_\varphi^2$ is the SNR in the PLL circuit, and σ_φ is a standard deviation of phase difference. The signal $i_{ei}(t)$ is sampled at time instants t_k

$$i_{ei}(t_k) = \pm RI(t_k)\cos\varphi(t_k) + x(t_k)\ , \tag{8}$$

and depending on value of $i_{ei}(t_k)$ the decision is made if one or zero is transmitted.

2.2. Channel model

Atmospheric turbulence causes the intensity variations of the received optical signal. Depending on the turbulence strength, different models can be used for describing statistical properties of optical signal intensity variations. For moderate to strong turbulence conditions the Gamma-Gamma PDF can be used for description of intensity variations. According to this model, the intensity fluctuation consists of small-scale and large-scale effects. The received signal irradiance I is a product of two statistically independent random processes I_x and I_y, $I = I_x I_y$. Both processes have Gamma distribution. Consequently, the resulting process I has the following Gamma-Gamma PDF given by

$$p_I(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta)/2-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}),\ I > 0\ , \tag{9}$$

where $\Gamma(.)$ denotes Gamma function, $K_\nu(.)$ is the modified Bessel function of the 2nd kind of order ν, and α and β, respectively, represent the effective number of large-scale and small-scale eddies of the scattering process. Parameters α and β are related to the atmospheric conditions. For weak, moderate and strong turbulence conditions the values of α and β are respectively (α, β)=(11.6, 10.1), (α, β)=(4, 1.9), (α, β)=(4.2, 1.4) [1].

2.3. Simulation model

The computer simulation was written in C^{++} programming language. The envelope I of the received signal irradiance is generated using relation $I=I_xI_y$, where I_x has the Gamma PDF with parameter α and mean value equal to 1, and I_y also has the Gamma PDF with parameter β and mean value equal to 1. The variables with the gamma PDF are generated using the algorithms presented in [9] and [10]. It can be shown that the variable I, generated in this way, has the PDF given by (9). The samples of random variable φ are generated by using acceptance/rejection method [8, p. 381-383]. The error probability is estimated based on 3×10^3 bit errors by using Monte Carlo simulations [8, p. 371-406].

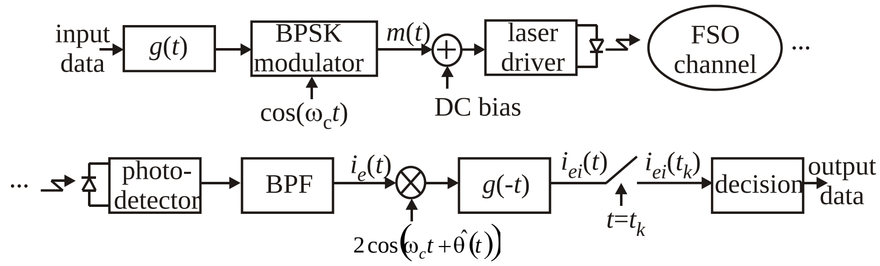

Fig. 1 Model of free space optical communication system

3. Simulations results

On the basis of the simulation model presented in the previous Section, we present simulations results here.

Figs. 2 and 3 present the BER dependence on average electrical signal-to-noise ratio for different values of standard deviation of phase difference jitter in the case of strong and weak turbulence conditions. One should notice that there are two regions of average electrical signal-to-noise ratio values. In the first region, BER decreases sharply with increasing average electrical signal-to-noise ratio. In the second region, BER remains constant with further increasing average electrical signal-to-noise ratio. This constant value of BER is called BER floor or irreducible BER. It is evident that average electrical signal-to-noise ratio does not influence this BER floor value. This BER floor can be decreased by decreasing standard deviation of phase noise. For example, in the case of weak turbulence condition, BER floor increases about 10^3 times with increasing σ_φ from 20^0 to 40^o.

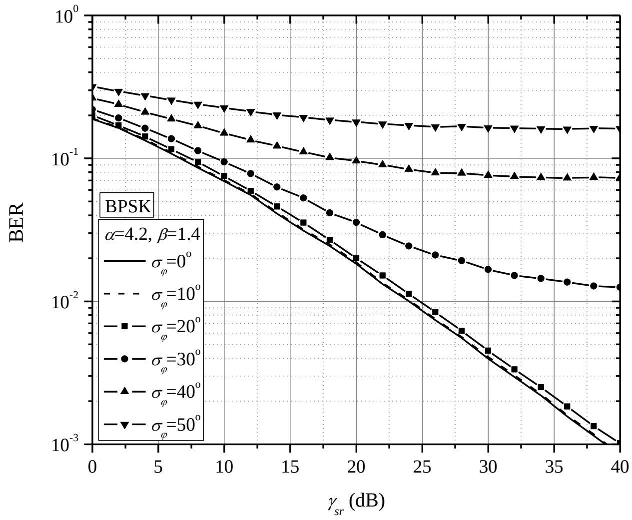

Fig. 2 BER dependence on average electrical SNR in strong turbulence conditions

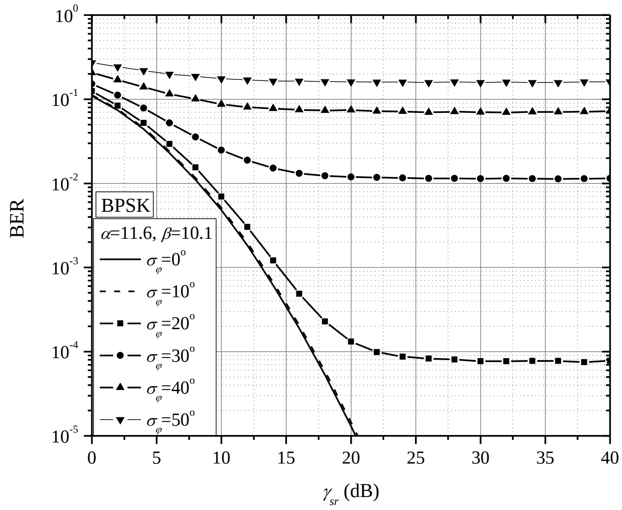

Fig. 3 BER dependence on average electrical SNR in weak turbulence conditions

Fig. 4 presents BER dependence on standard deviation of phase noise for different values of average electrical signal-to-noise ratio. It should be noticed that BER increases with increasing standard deviation of phase noise. In order words, this figure illustrates receiver sensitivity to standard deviation of phase noise. Based on the results presented here, it is possible to estimate the maximum value of standard deviation of phase noise under condition that previously fixed BER not to be exceeded in given turbulence and average SNR conditions. That is a very useful parameter in designing PLL circuits.

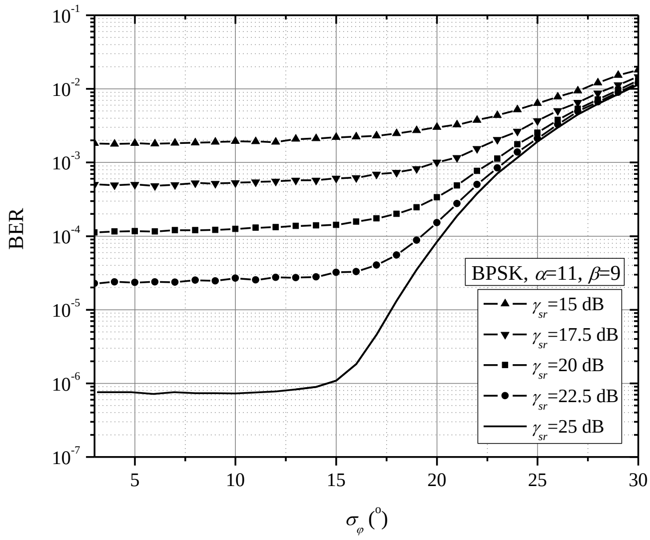

Fig. 4 BER dependence on standard deviation of phase noise for different values of average electrical SNR

4. Conclusion

Taking the imperfect reference signal recovery into account, we have analyzed reception of BPSK pre-modulated SIM signals transmitted over FSO channel with Gamma-Gamma turbulence. The flexible simulation model has been developed for estimating BER for different values of receiver and channel parameters. The simulation model enables one to determine BER values for different turbulence conditions and average electrical signal-to-noise ratios. A significant phenomenon has been noticed. In contrast to BPSK SIM FSO systems with perfect received signal estimation, where BER decreases in the whole range of average electrical SNR values, here BER decreases with average electrical SNR increasing in the low and moderate average SNR values range. With further increasing average SNR, the BER remains constant and this irreducible error floor does not depend on SNR. This BER floor is important system characteristic. On the basis of the results presented here it is possible to determine the maximum permitted value of standard deviation of phase noise in order to ensure that previously defined BER values is not exceeded for given values of receiver and channel parameters. This maximum permitted value of standard deviation of phase noise is a useful parameter for constructing PLL circuit.

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