Performance of Free Space Optical Communication in Malaga Channel with Zero/Non-Zero Boresight Pointing Error

Marko Smilić, Dejan Milić, Petar Spalević and Zorica Nikolić

***Abstract*—In this paper, the bit error rate (BER) of intensity modulated Free-Space Optical (FSO) with direct detection (IM/DD) in single–input single–output (SISO) over Malaga atmospheric turbulence channels has been investigated. Analytical expressions in closed form for probability density function (PDF) over Malaga atmospheric turbulence channels for zero boresight pointing error and non-zero boresight pointing error are represented. Also, analytical expression in closed form for BER for zero boresight pointing error and non-zero boresight pointing error are given. The results are evaluated numerically and graphically presented in terms of BER and power penalty due to zero boresight pointing error and non-zero boresight pointing error.**

***Index Terms*—Probability Density Functions, Bit Error Rate, Free Space Optics, Zero Boresight Pointing Error, Non-Zero Boresight Pointing Error, Power Penalty.**

I. INTRODUCTION

The study of wireless optical systems is multidisciplinary involving a wide range of areas including: optical design, optoelectronics, electronics design, channel modelling, communications and information theory, modulation and equalization, wireless optical network architectures among many others [1]. In recent times, free-space optical (FSO) or optical wireless communication systems have gained an increasing interest due to its advantages including higher bandwidth and higher capacity compared to the traditional RF communication systems. In addition, FSO links are license-free and hence are cost-effective relative to the traditional RF links. It is a promising technology as it offers full-duplex Gigabit Ethernet throughput in certain applications and environment offering a huge license-free spectrum, immunity to interference, and high security [2]. Commercial FSO systems mostly deploy the intensity-modulation with direct detection (IM/DD) and the on-off keying (OOK), primarily because of the simplicity of its design and implementation [3].

During transmission, transmitted signal is exposed to various effects such are atmospheric turbulence, irradiance, misalignment between the transmitter and receiver (pointing error) and scintillation index. These effects influence the performances of the transmitted signal.

There are many models that are used for modeling transmission under the influence of atmospheric turbulences. In this paper, Malaga model of atmospheric turbulence is used [4]. Malaga model represents a general model of atmospheric turbulences and it can be reduced to other turbulences models such as K turbulence model, HK turbulence model, Gamma and Gamma-Gamma turbulence models, Exponential-Weibull turbulence models etc.

In addition to atmospheric turbulence, the pointing error also affects on the system performance. A pointing error occurs due to the missaligment between the transmitter and the receiver. Pointing error consists of two components: laser precision (boresight) and jitter. This paper consideres system performance in terms of BER and power penalty under the influence of the Malaga atmospheric turbulence model for zero boresight pointing error and non-zero boresight pointing error. Impacts of zero boresight pointing error and non-zero boresight pointing error on FSO transmission over Malaga model atmospheric turbulence are presented in [5], [6], [7], [8].

It has already been said that the Malaga model represent a general model of atmospheric turbulence. Other models of atmospheric turbulence can be obtained from the Malaga model. The impact of pointing error on BER performance for K, HK, Exponential-Weibull, Log-Normal, Gamma-Gamma atmospheric turbulence model are presented in [9], [10], [11], [12], [13].

Bit error rate (BER) of intensity modulated FSO with direct detection (IM/DD) in single–input single–output (SISO) over Gamma-Gamma atmospheric turbulence channels are presented in [14], [15], [16].

In this paper, BER performance are analyzed for FSO system which is exposed to Malaga atmospheric turbulence for zero boresight and non-zero boresight pointing error. Closed form expression for probability density function and BER under mentioned conditions are given. Numerical result are graphically presented and explained. BER performance was considered in terms of power penalty.

II. SYSTEM MODEL

We consider a FSO system with direct detection (IM/DD) in single–input single–output (SISO) over Malaga atmospheric turbulence channels. During the transmission between transmitter and receiver, the laser beam is exposed to atmospheric turbulence and pointing error. At the transmitter, information bits are modulated by an electro-optical modulator IM/OOK whose output represents the

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Marko Smilić is with the Faculty of Natural Sciences and Mathematics, University of Priština, Lole Ribara 29, 38220 Kosovska Mitrovica, Serbia (e-mail: marko.smilic@.pr.ac.rs).

Dejan Milić is with the Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia (e-mail: dejan.milic@elfak.ni.ac.rs).

Petar Spalević is with the Faculty of Technical Sciences, University of Priština, Kneza Miloša 7, 38220 Kosovska Mitrovica, Serbia (e-mail: petar.spalevic@pr.ac.rs).

Zorica Nikolić is with the Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia (e-mail: zorica.nikolic@elfak.ni.ac.rs).

intensity of the laser source. Next, the direction and the size of the laser beam are determined by the transmitting telescope which forwards the optical signal to the receiver over the atmospheric channel. At the receiver, the received laser beam is narrowed by telescope and passed to the photodetector, which is in charge of the optical to electrical signal conversion. After conversion, electrical signal is:

$$y = Ix + n \tag{1}$$

where x represent the binary transmitted signal, I is the normalized channel fading coefficient considered to be constant over a large number of transmitted bits, and n is AWGN with variance σ_s^2. We are considering the OOK scheme and transmitted signal can have two probabilities: the probability “on” bits or the probability “off” bits. When the transmitted signal has information “on” bits then it has value $2P_t$, whereas when the transmitted signal has an information “off”, it has a value 0. P_t represents the average transmitted optical power. After conversion, electrical signal for state “on” is $2P_tRI + n$, and for state “off” is $0 + n$. The intensity of the signal can be expressed as $I = I_a I_l I_p$, where I_a represents atmospherics turbulence loss factor, I_p represents pointing error loss factor and I_l is path loss.

A. Atmospheric turbulence model

Malaga model is given in [4]:

$$f_a(I_a) = A\sum_{k=1}^{\beta} a_k I_a^{\frac{\alpha+k}{2}-1} K_{\alpha-k}\left(2\sqrt{\frac{\alpha\beta I_a}{\gamma\beta+\Omega^{`}}}\right) \tag{2}$$

where

$$A \triangleq \frac{2\alpha^{\frac{\alpha}{2}}}{\gamma^{1+\frac{\alpha}{2}}\Gamma(\alpha)}\left(\frac{\gamma\beta}{\gamma\beta+\Omega^{`}}\right)^{\beta+\frac{\alpha}{2}} \tag{3}$$

$$a_k \triangleq \binom{\beta-1}{k-1}\frac{\left(\gamma\beta+\Omega^{`}\right)^{1-\frac{k}{2}}}{\Gamma(k)}\left(\frac{\Omega^{`}}{\gamma}\right)^{k-1}\left(\frac{\alpha}{\beta}\right)^{\frac{k}{2}} \tag{4}$$

The parameters α and β represent the effective numbers of small-scale and large scale cells, respectively, and can be related to the atmospheric conditions. Parameters α and β represents as:

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

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

for plane wave propagation and zero inner scale is assumed [2]. σ_R^2 represents the Rytov variance and is used as a metric of the strength of turbulence. It is given by:

$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \tag{7}$$

where $k = 2\pi/\lambda$ is the wave-number, λ is the wavelength, L is the propagation distance, and C_n^2 is the refractive index structure parameter, which typically varies from $10^{-17} m^{-2/3}$ to $10^{-13} m^{-2/3}$ as turbulence strength varies from weak to strong conditions [15].

B. Path loss

Path loss, I_l, can be described by the exponential Beers-Lambert Laws as:

$$I_l(L) = e^{-\sigma L} \tag{8}$$

where L denotes the propagation distance and σ is the attenuation coefficient.

C. Pointing error

Pointing error also affects on transmission performances. In case of zero boresight pointing error, I_p, we are presented next model:

$$f_{I_p}(I_p) = \frac{\xi^2}{A_0^{\xi^2}} I_p^{\xi^2-1}\ ,\ 0 \le I_p \le A_0 \tag{9}$$

$$f_{I_p}(I_p) = \frac{\xi^2 e^{-\frac{s^2}{2\sigma_s^2}}}{A_0^{\xi^2}} I_p^{\xi^2-1} I_0\left(\frac{s}{\sigma_s^2}\sqrt{\frac{-\omega_{Leq}^2 \ln\left(\frac{I_p}{A_0}\right)}{2}}\right) \tag{10}$$

where $\xi = \omega_{Leq}/2\sigma_s$ is the ratio between the equivalent beam radius at the receiver ω_{Leq} and the pointing error displacement standard deviation at the receiver σ_s, s is the boresight displacement, σ_s^2 is the jitter variance at the receiver, $I_0(\cdot)$ is the modified Bessel function of the first kind with order zero. $A_0 = \left(erf(v)\right)^2$ is the fraction of the collected power where $v = \sqrt{\pi}a/\sqrt{2}\omega_L$ with $erf(\cdot)$ denoting the error function, where as the square of the equivalent beam width is given by:

$$\omega_{Leq}^2 = \omega_L^2 \frac{\sqrt{\pi}erf(v)}{2ve^{-v^2}} \tag{11}$$

D. Probability Density

Probability Density Function of signal intesity I for zero boresight pointing error and non-zero boresight pointing error are given in [17] and [7] respectively.

$$f_I(I)=\frac{\xi^2 A}{2I}\sum_{k=1}^{\beta}a_k\left(\frac{\alpha\beta}{\gamma\beta+\Omega'}\right)^{-\frac{\alpha+k}{2}}\times G_{1,3}^{3,0}\left(\frac{\alpha\beta}{\gamma\beta+\Omega'}\frac{I}{A_0 I_l}\middle|\begin{matrix}\xi^2+1\\ \xi^2,\alpha,k\end{matrix}\right) \tag{12}$$

$$f_I(I)=\frac{2\pi\xi^2 Ae^{-\frac{s^2}{2\sigma_s^2}}}{\omega_{Leq}^2}\sum_{k=1}^{\beta}\frac{a_k I^{\frac{\alpha+k}{2}-1}}{\left(A_0 I_l\right)^{\frac{\alpha+k}{2}}\sin(\pi(\alpha-k))}\times \sum_{p=0}^{P}\left\{\frac{\left(\frac{\alpha\beta I}{(\gamma\beta+\Omega')A_0 I_l}\right)^{p-\frac{\alpha-k}{2}}}{\Gamma\left(p-(\alpha-k)+1\right)p!}\left(-\frac{\omega_{Leq}^2}{4(p+k-\xi^2)}e^{-\frac{\omega_{Leq}^2 s^2}{8(p+k-\xi^2)\sigma_s^4}}\right)-\frac{\left(\frac{\alpha\beta I}{(\gamma\beta+\Omega')A_0 I_l}\right)^{p+\frac{\alpha-k}{2}}}{\Gamma\left(p+(\alpha-k)+1\right)p!}\left(-\frac{\omega_{Leq}^2}{4(p+\alpha-\xi^2)}e^{-\frac{\omega_{Leq}^2 s^2}{8(p+\alpha-\xi^2)\sigma_s^4}}\right)\right\} \tag{13}$$

The received instantaneous SNR is defined as:

$$g=\frac{\left(2P_t RI\right)^2}{2\sigma_n^2} \tag{14}$$

where σ_n^2 denotes Additive White Gaussian Noise (AWGN). Average electrical SNR can be defined as:

$$\mu=\frac{\left(2P_t R\right)^2}{2\sigma_n^2}E\left[I\right] \tag{15}$$

where $E[.]$ is the statistical expectation. Based on PDF of signal intensity in (12) and average electrical SNR in (15), average electrical SNR can be determined as:

$$\mu=\frac{\left(2P_t R\right)^2}{2\sigma_n^2}A_0^2 I_l^2\kappa^2\left(\gamma+\Omega'\right)^2 \tag{16}$$

The Probability Density Function of SNR for zero boresight pointing error is:

$$f_g(g)=\frac{\xi^2 A}{4g}\sum_{k=1}^{\beta}a_k\left(\frac{\alpha\beta}{\gamma\beta+\Omega'}\right)^{-\frac{\alpha+k}{2}}\times G_{1,3}^{3,0}\left(\frac{\alpha\beta\kappa\left(\gamma+\Omega'\right)}{\gamma\beta+\Omega'}\sqrt{\frac{g}{\mu}}\middle|\begin{matrix}\xi^2+1\\ \xi^2,\alpha,k\end{matrix}\right) \tag{17}$$

III. BER PERFORMANCE ANALYSIS

In this paper, the bit error rate (BER) of intensity modulated FSO using direct detection (IM/DD) in single–input single–output (SISO) with OOK over Malaga atmospheric turbulence channels has been investigated. The receiver in a digital communication system must make two decisions: (1) when to sample the received data and (2) whether the sampled value represents a binary 1 (“on”) or 0 (“off”). BER is expressed as:

$$P_e=P\left(1\right)P\left(0|1\right)+P\left(0\right)P\left(1|0\right) \tag{18}$$

where $P\left(1\right)$ and $P\left(0\right)$ represent the probabilities of transmitting „on“ and „off“ bits, respectively. The probability of detecting “off” bit when “on” bit is sent is $P\left(0|1\right)$, and $P\left(1|0\right)$ is the otherwise. It is considered that $P\left(1\right)=P\left(0\right)=0.5$ as is explained in [14]. For this case, BER can be presented as:

$$P_{e|I}=\frac{1}{2}erfc\left(\frac{Q\left(I\right)}{\sqrt{2}}\right) \tag{19}$$

where the parameter Q is

$$Q=\frac{2P_t RI-0}{\sigma_n} \tag{20}$$

The average BER of Malaga atmospheric turbulence channel according to signal intensity I and SNR are given, respectively:

$$P_e=\frac{1}{2}\int_0^{\infty}erfc\left(\frac{2P_t RI}{\sqrt{2}\sigma_n}\right)f_I\left(I\right)dI \tag{21}$$

$$P_e=\frac{1}{2}\int_0^{\infty}erfc\left(\frac{g}{\sqrt{2}}\right)f_g\left(g\right)dg \tag{22}$$

If we represented $erfc(\cdot)$ as special case of MeijerG function according to [18] and [19] and substituting in (21 or 22) along with expression (12 or 17), integral from (21 or 22) can be solved from relation [19]. Closed form expression for zero boresight pointing error for ABER is given:

$$P_e=\frac{2^{\alpha}\xi^2 A}{32\pi\sqrt{\pi}}\sum_{k=1}^{\beta}2^k\left(\frac{\alpha\beta}{\gamma\beta+\Omega'}\right)^{-\frac{\alpha+k}{2}}a_k\times G_{7,4}^{2,6}\left(\frac{8R^2P_t^2A_0^{\,2}I_l^2}{\sigma_n^2}\left(\frac{\gamma\beta+\Omega'}{\alpha\beta}\right)^2\middle|\begin{matrix}\Xi\\ \Psi\end{matrix}\right) \tag{23}$$

where $\Xi=\frac{1-\xi^2}{2},\frac{2-\xi^2}{2},\frac{1-\alpha}{2},\frac{2-\alpha}{2},\frac{1-k}{2},\frac{2-k}{2},1$, and $\Psi=0,\frac{1}{2},\frac{-\xi^2}{2},\frac{1-\xi^2}{2}$. Average BER according to SNR is

$$P_e=\frac{2^{\alpha}\xi^2 A}{32\pi\sqrt{\pi}}\sum_{k=1}^{\beta}2^k\left(\frac{\alpha\beta}{\gamma\beta+\Omega'}\right)^{-\frac{\alpha+k}{2}}a_k\times G_{4,7}^{6,2}\left(\frac{\alpha^2\beta^2\kappa^2\left(\gamma+\Omega'\right)^2}{4\mu\left(\gamma\beta+\Omega'\right)^2}\middle|\begin{matrix}\Xi\\ \Psi\end{matrix}\right) \tag{24}$$

where

$$\Xi = 1, \frac{1}{2}, \frac{\xi^2+1}{2}, \frac{\xi^2+2}{2},$$

$$\Psi = \frac{\xi^2}{2}, \frac{\xi^2+1}{2}, \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{k}{2}, \frac{k+1}{2}, 0 .$$

Average BER for non-zero boresight pointing error is calculated and represented in closed form as:

$$\begin{aligned} P_e = {} & \frac{\sqrt{\pi}\xi^2 A e^{-\frac{s^2}{2\sigma_s^2}}}{\omega_{Leq}^2} \sum_{k=1}^{\beta} \frac{a_k}{\left(A_0 I_l\right)^{\frac{\alpha+k}{2}} \sin(\pi(\alpha-k))} \times \\ & \sum_{p=0}^{P} \left\{ \frac{\left(\frac{\alpha\beta}{(\gamma\beta+\Omega^{'})A_0 I_l}\right)^{p-\frac{\alpha-k}{2}}}{\Gamma\left(p-(\alpha-k)+1\right) p!} \left(\frac{R^2 P_t^2}{\sigma_n^2}\right)^{-\left(\frac{p+k+1}{2}\right)} \times \right. \\ & \frac{\Gamma\left(\frac{p+k+1}{2}\right)\Gamma\left(\frac{p+k+2}{2}\right)}{\Gamma\left(\frac{p+k+3}{2}\right)} \times \\ & \left(-\frac{\omega_{Leq}^2}{4(p+k-\xi^2)} e^{-\frac{\omega_{Leq}^2 s^2}{8(p+k-\xi^2)\sigma_s^4}}\right) - \\ & \frac{\left(\frac{\alpha\beta}{(\gamma\beta+\Omega^{'})A_0 I_l}\right)^{p+\frac{\alpha-k}{2}}}{\Gamma\left(p+(\alpha-k)+1\right) p!} \left(\frac{R^2 P_t^2}{\sigma_n^2}\right)^{-\left(\frac{p+\alpha+1}{2}\right)} \times \\ & \frac{\Gamma\left(\frac{p+\alpha+1}{2}\right)\Gamma\left(\frac{p+\alpha+2}{2}\right)}{\Gamma\left(\frac{p+\alpha+3}{2}\right)} \times \\ & \left. \left(-\frac{\omega_{Leq}^2}{4(p+\alpha-\xi^2)} e^{-\frac{\omega_{Leq}^2 s^2}{8(p+\alpha-\xi^2)\sigma_s^4}}\right) \right\} \end{aligned} \tag{25}$$

BER is determined by the standard deviation of the noise and the distance between the signal levels. $P(0)$ is ideally equal to zero, making the optimum extinction ratio infinite. When the extinction ratio is not optimum, however, the transmitted power must be increased in order to maintain the same BER. This increase in transmitted power due to non-ideal values of extinction ratio is called the "power penalty."

Some paper explained analysis of the influence of communication parameters of FSO channels on the reception quality in terms of BER and power penalty [20], [21], [22], [23], [24].

Extinction ratio is an important parameter included in the specifications of most fiber-optic transceivers. The purpose of this application note is to show how the optical extinction ratio is defined and to demonstrate how variations in extinction ratio affect the performance of digital optical communication systems. The ratio between the "one" level and the "zero" level is defined as the "extinction ratio," and is represented by the symbol r_e.

$$r_e = \frac{P_1}{P_0} \tag{26}$$

From expression (19), Q factor can be written in terms of BER as:

$$Q = \sqrt{2} erfc^{-1}\left(2P_e\right) \tag{27}$$

And power penalty can be calculated in function of extinction ratio as:

$$PP\left(r_e\right) = \frac{Q}{2P_t R}\left(\frac{r_e+1}{r_e-1}\right) \tag{28}$$

IV. NUMERICAL RESULTS

Figure 1 shows the dependence of the BER of the FSO system with IM/DD and OOK modulation for zero boresight pointing error and non-zero boresight pointing error in the function of transmitting optical power for different values of link propagation distance L. As is shown in figure, BER performaces are worse for non-zero boresight pointing error than for zero boressight pointing error. For shorter link distance, BER performance for both pointing error are better. With increasing the distance of link, BER performance for both pointing error decreasing.

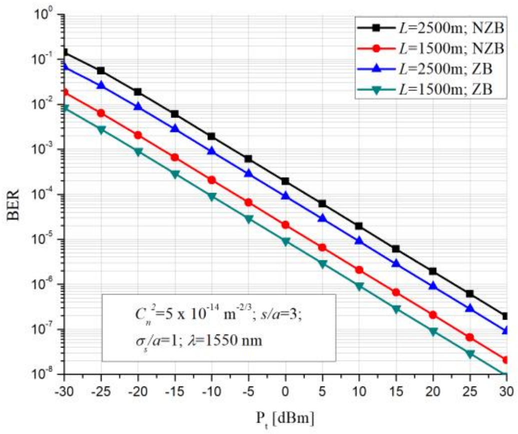

Fig. 1. Average BER for zero boresight pointing error and non-zero boresight pointing error depending of the transmitted optical power P_t for different link distance L.

Figure 2 represent BER performance in dependence of normalized optical beam width at reception. The lower value of radius of detector a, or a bigger value of optical beam width at the distance L from transmitter w_L, i.e. higher value of w_L/a lead to a poorer BER performances.

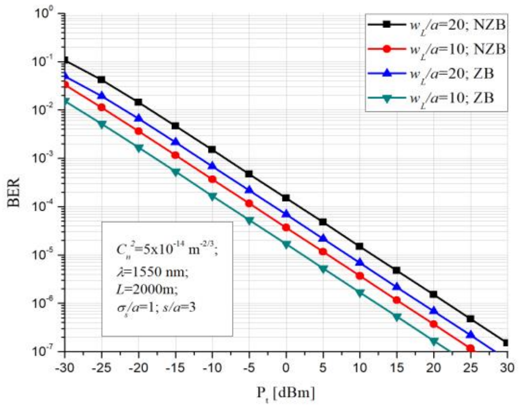

Fig. 2. Average BER for zero boresight pointing error and non-zero boresight pointing error depending of the transmitted optical power P_t for different ratio between optic beam width and radius of detector.

As is presented in Figure 3, small changes in extinction ratio can make a relatively large difference in the power required to maintain a constant BER. With increasing an extinction ratio, power penalty decreasing, and for decreasing extinction ratio, power penalty increasing. Values of extinction ratio and power penalty for zero boresight pointing error and non-zero boresight pointing error are given in Table I.

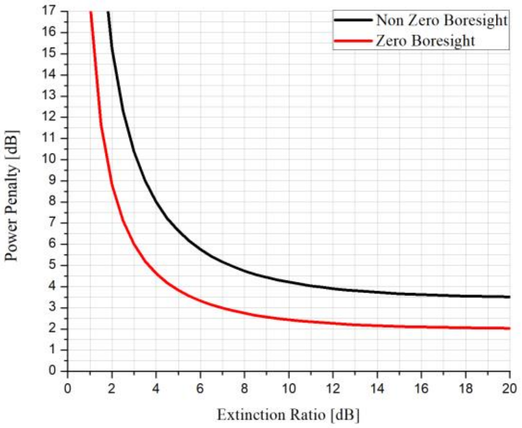

Fig. 3. Power penalty for zero boresight pointing error and non-zero boresight pointing error depending of extinction ratio.

TABLE I

POWER PENALTY FOR POINTING ERROR IN FUNCTION OF EXTINCTION RATIO

Extinction ratio [dB]	Power penalty [dB]	
	Zero Boresight	Non-Zero Boresight
2	8.81	15.24
3	6	10.37
4	4.63	8
5	3.84	6.63
6	3.33	5.76
7	2.99	5.16
8	2.745	4.74
10	2.44	4.21
15	2.12	3.67
20	2.03	3.52

V. CONCLUSION

In this paper, we observe the BER performance of FSO system using IM/DD with OOK. The atmospheric turbulence is modeled by Malaga distribution which is an appropriate model in wide range of atmospheric conditions. Zero boresight pointing error and non-zero boresight pointing error are considered. The receiver noise is modeled as additive white Gaussian noise. The BER expression in closed form are derived and numerical results are presented, while the effects of various link conditions are observed. Results of transmitted power due to non-ideal values of extinction ratio are presented. BER performances in terms of power penalty are discussed.

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