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# On the Transmission of Colour Image Over Double Generalized Gamma FSO Channel

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***Abstract*—In this paper performance analysis of colour image Free Space Optics (FSO) transmission over Double Generalized Gamma (DGG) turbulence communication channel is carried out. At the reception side, we have used an average bit error rate (ABER) for reconstructed image performance measure, as the function of FSO link transmission parameters, such as propagation distance, Rytov variance and turbulence shaping and severity parameters ($\gamma_1$, $\gamma_2$, $m_1$, $m_2$). Obtained results cover a large number of colour image FSO transmission scenarios, for Gamma-Gamma, Double-Weibull and *K* turbulence models channels considered as special cases.**

***Index Terms*—Free-space optical communication; channel models; double generalized gamma channel; image processing.**

## I. INTRODUCTION

Development of FSO technology allows high-speed transmission over free space [1], [2]. Widespread use of FSO communication systems has arisen due to its obvious advantages, which especially occur in satellite communications, terrestrial and last-mile connections. Main advantages over RF systems (beyond high speed transmission), are the absence of co-channel interference and crosstalk during transmission of high data flow and usage of small transmission power and no need for spectrum licensing. One of the basic assumption for successful application of FSO system is the existence of Line of Sight (LOS) between transmitter and receiver, although there also may exist relay realizations of FSO systems. However, there are also a few drawbacks that can significantly impair performance of FSO transmission. One of them are weather conditions along transmission path, manifested in the form of scintillation, random fluctuations of the irradiation of optical beam caused by turbulences. Namely, temporal and spatial fluctuations that occur are consequence of the variations of refraction index (caused by fog, rain, haze), which manifest as irradiation fluctuations of received FSO signal [3]–[5]. The scintillation index is the measure of the turbulence strength, where lower values lead to less intensity variations and, vice versa, higher index values result in the higher values of turbulences. Refraction index $C_n^2$ [6], is a variable that depends on the geographic location, altitude and time of the day. The refraction deviation index results in scintillation, the deviation and spread of the beam. The characteristic values of refraction index in terrestrial communication are in the range $10^{-17}$ - $10^{-13}$ $m^{-2/3}$ [4], [5], while in moderate turbulences it has a value of about $10^{-15}$ $m^{-2/3}$ [7]. In order to obtain accurate modelling of FSO propagation, various mathematical and numerical models, have been provided in the literature. Weibull distribution model is mostly used for modelling of scintillation of signal with different intensities of turbulences and is often applied in systems with large aperture on the receiving side [8]. Log-Normal distribution model [9] is used for modelling scintillation related to the regimes of weak atmospheric turbulence [3], [10]. Rician distribution model is used for description of scintillation that occurs in terrestrial communication channels in sparsely populated areas and suburbs [11]. Gamma-Gamma distribution is a very simplified model of scintillation that can be applied for other regimes of turbulences [12]. However, recently Double Generalized Gamma (DGG) turbulence model [13], [14] has been considered since it generalizes many existing turbulence channel model and provides an excellent fit to the plane and spherical waves simulation data. This model can be reduced to other previously mentioned models (except for the Rician turbulence model) of scintillation by setting the corresponding values to the DGG model parameters. In [15] FSO image transmission over Rician turbulence channel was considered, so this analysis can be considered as an extension and supplementation of results provided in [15].

In this paper we have analysed performances of image (colour image-fire) transmission over DGG channel as the function of FSO transmission parameters within its theoretic boundaries. In the Section II basic assumptions of Double Generalized Gamma FSO transmission have been presented.

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Obtained simulation results and performance analysis are presented in the Section III. Concluding remarks are given in the Section IV.

## II. SYSTEM MODEL

At the aperture plane of the receiver, the received FSO signal is modeled as

$$E_r(t,r)=u_s(t)\exp(j2\pi f_c t+\theta(t))\times\exp[\chi(r)+j\phi(r)], \quad (1)$$

where $r$ is the position vector on the receive aperture plane, $f_c$ is the optical carrier frequency, and $u_s(t)\exp(j\theta(t))$ denotes the complex envelope of the modulation signal. Here, $\chi(r)$ is the turbulence-induced amplitude fluctuations and $\phi(r)$ is the phase variations of the channel.

At the output photocurrent can be modelled as

$$y_T(t)=x_T(t)+n_T(t), \quad (2)$$

where $n_T(t)$ denotes total noise at the receiver expressed as [16], [17]

$$n(t)=n_{Th}+n_{sh}, \quad (3)$$

where $n_{Th}$ denotes thermal noise and $n_{sh}$ denotes shot noise. Thermal noise can be modeled as the stationary Gaussian random process with the zero-mean value expressed as [16], [17]

$$\sigma_{Th}^2=4k_B\frac{T}{R_L}F_n\Delta f, \quad (4)$$

where $k_B$ denotes Boltzmann constant and $F_n$ denotes amplifier noise figure, $T$ and $R_L$ are temperature and load resistance respectively, $\Delta f$ is the effective noise bandwidth. The effective bandwidth is dependent on the bit rate, $R_b$, as $\Delta f=R_b/2$.

Shot noise can be modelled as the stationary zero-mean Gaussian random process expressed as [16], [17]

$$\sigma_{sh}^2=2qg^2F_ARP_tmI\Delta f, \quad (5)$$

where $q$ represents an electron charge, $g$ and $R$ represent gain and responsivity, respectively, $P_t$ denotes transmitted optical power, $m$ denotes modulation index, $I$ represent accounted normalized irradiance, and $F_A$ denotes the excess noise factor expressed as [17]

$$F_A=k_Ag+(1-k_A)(2-1/g), \quad (6)$$

where $k_A$ is the ionization factor.

The total noise is obtained as a sum of thermal and shot noise variances and expressed as

$$\sigma_n^2=\sigma_{Th}^2+\sigma_{sh}^2=4k_B\frac{T}{R_L}F_n\Delta f+2qg^2F_ARP_tmI\Delta f, \quad (7)$$

Information carrying part of signal can be modeled as

$$x_T(t)=\frac{e\eta\pi}{2hf_c}AD^2u_s(t)\times\mathrm{Re}\{I\exp(j2\pi f_{IF}t+\theta_{IF}(t))\}, \quad (8)$$

where $f_{IF}=f_c-f_{LO}$ is the equivalent signal frequency, $f_{LO}$ is local oscillator frequency, $\theta_{IF}$ is the equivalent signal phase and $\alpha$ represents the effective FSO fading fluctuation of the channel. As shown in [14], in order to model simultaneous effects of turbulence-induced amplitude fluctuations and phase aberrations, the Probability Density Function (PDF) of FSO fading amplitude will be modelled with Double Generalized Gamma distribution, as

$$f_I(I)=\frac{\gamma_2 pp^{m_2-1/2}q^{m_1-1/2}2\pi^{1-(p+q)/2}I^{-1}}{\Gamma(m_1)\Gamma(m_2)}\times$$
$$\times G_{p+q,0}^{0,p+q}\left[\left(\frac{\Omega_2}{I^{\gamma_2}}\right)^p\frac{p^pq^q\Omega_1^q}{m_1^qm_2^p}\middle|\begin{matrix}\Delta(q:1-m_1), & \Delta(p:1-m_2)\\ - & \end{matrix}\right], \quad (9)$$

where $G_{p,q}^{m,n}(x)$ is the Meijers G-function defined in [18], $\Gamma(x)$ denotes special Gamma function [18], $p$ and $q$ are positive integer numbers that satisfy $p/q=\gamma_1/\gamma_2$, and $\Delta(j;x)\triangleq x/j,\ldots,(x+j-1)/j$. Parameters $\gamma_1$, $\gamma_2$, $\Omega_1$, $\Omega_2$, $m_1$, $m_2$, are parameters of Generalized Gamma distributions, which model statistically independent random processes arising respectively from large scale and small scale turbulent eddies. Parameters $m_1$, $m_2$ are shaping parameters defining the turbulence-induced fading, while parameters $\gamma_1$, $\gamma_2$ are defining the severity levels of statistically independent irradiances forming the DGG. These parameters, and their corresponding constant values along the FSO can be identified using the moments of small and large scale irradiance fluctuations and are directly tied to the atmospheric parameters (the ratio of Fresnel zone, Rytov variance, $\sigma^2R_{ytov}$, proportional to the scintillation index, and function of wavenumber, $k=2\pi/\lambda$, the refractive index structure constant, and the propagation distance) as shown in (9a), (9b) and (10) from [13]. Parameters $\Omega_1$ and $\Omega_2$ depend on and directly are tied to the atmospheric conditions. Assuming a plane wave when inner scale effects are considered, the variances for the large-scale and the small-scale scintillations are given by [13] in the forms of the ratio of Fresnel zone to finite inner scale and Rytov variance ($\sigma^2_{Rytov}$)

$$\sigma_{Rytov}^2=1.23C_n^2k^{7/6}L^{11/6}, \quad (10)$$

where $k=2\pi/\lambda$ is the wave-number, $\lambda$ is the wavelenght, $L$-propagation distance and $C_n^2$ refraction index.

Finally, received instantaneous SNR of the system after demodulation is given as

$$\gamma=\frac{P_x}{2\sigma_n^2}=\frac{P_x}{2(\sigma_{Th}^2+\sigma_{sh}^2)}=$$
$$=\frac{E^2I_s}{2(4k_B\frac{T}{R_L}F_n\Delta f+2qg^2F_ARP_tmI\Delta f)}I^2, \quad (11)$$

where $E^2=\frac{e\eta\pi}{2hf_c}AD^2$ and $I_s=|u_s(t)|^2$ is the average intensity of the optical field, and $P_x$ is the output signal power.

Algorithm for simulating FSO transmission of colour image (image of fire) is accomplished in steps explained in [19].

## III. SIMULATION AND PERFORMANCE ANALYSIS

To simulate FSO transmission of the fire images over the Double Generalized Gamma turbulence fading channel the following experiment is conducted:

*Step 1*: The original colour images (Fig. 1(a) and Fig. 1(b)) are imported from the base and the source coding is done.

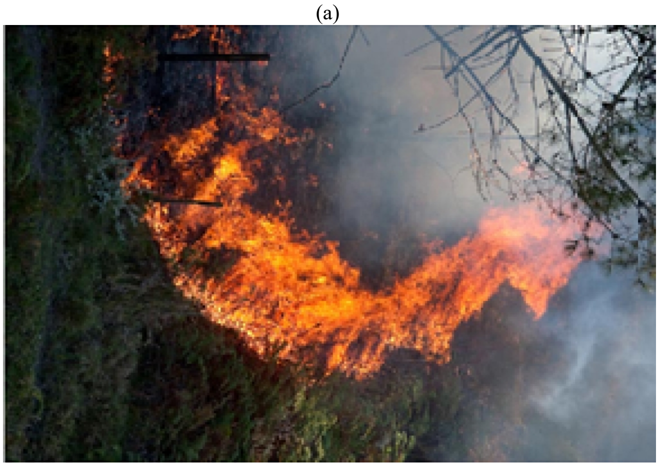
*Step 2*: The obtained binary signal was transmitted by BPSK modulation.

*Step 3*: The BPSK-modulated signal is transmitted over the DGG fading channel with added noise and with different values of the Rytov variance.

*Step 4*: At the receiver side, the signal is decoded and images were reconstructed.

*Step 5*: Obtained images are analysed.

(a)



(b)

Fig. 1. Basic Images: a) im1; b) im2.

As the quality measure for the image transmission Bit Error Rate (BER) is used, defined as

$$BER = \frac{\sum_{ijl} \left[ (x_{ij})_l \right]_2 \oplus \left[ (y_{ij})_l \right]_2}{M \times N}, \tag{12}$$
$$i = 1...M,\ j = 1..N,\ l = 1...n.$$

where $x_{ij}$ - pixel of original image, $y_{ij}$ - pixel of transmitted image, $n$-number of bits, $M \times N$-the size of the image, and $\oplus$ denotes EXOR operator over each of $n$ pair of bits from $x_{ij}$ and $y_{ij}$.

For the purpose of the experiment we have used the image set shown in the Fig. 1 [20]. The values of the Rytov variance (obtained for different values of propagation distance and refraction index) $\sigma^2_{Rytov}$ are varied in the interval {0.3, 0.83, 1.0, 1.2, 2.29, 3.96} and applied for each transmitted image.

In the Fig. 2–Fig. 4 performance of reconstructed Image im1 is shown, as the function of refraction index and propagation length change for the given sets of parameters $\gamma_1$, $\gamma_2$, $m_1$, $m_2$ defined to match most common scenarios of plane wave turbulence as explained in [13]. From the figures it can be seen how performance deteriorates as the length of FSO propagation link increases. Also it is visible how change of refraction structure parameter $C_n^2$ affects the BER for given turbulence channel performance. The increase of the parameter $C_n^2$ value, causes further increase of the BER for all observed values of SNR.

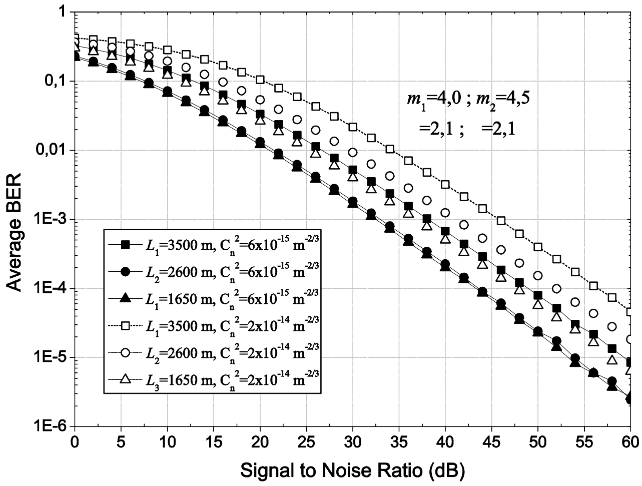



Fig. 2. Average BER for different value of propagation $L$ and different values of refraction index, for the considered set of turbulence channel parameters.

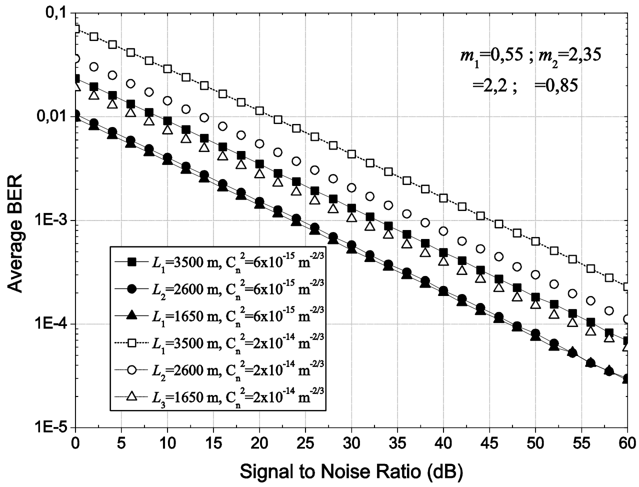



Fig. 3. Average BER for different values of propagation $L$ and different values of refraction index, for the considered set of turbulence channel parameters.

In the Fig. 5 BER performance of reconstructed Image 1 are given, in the function of turbulence shaping and severity parameters $\gamma_1$, $\gamma_2$, $m_1$, $m_2$. From the figure it can be seen that decrease of the parameter $\gamma_2$ leads to the increase of the BER for all the observed values of SNR (curve denoted with -☆- in comparison with curve denoted with -■-). It can be seen that, the increase of the parameter $m_2$ leads to decrease of the BER for all the observed values of SNR (curve denoted with -▲- in comparison with curve denoted with -■-), while the increase of the parameter $m_1$ leads to the increase of the BER (curve denoted with -●- in comparison with curve denoted with -■-).

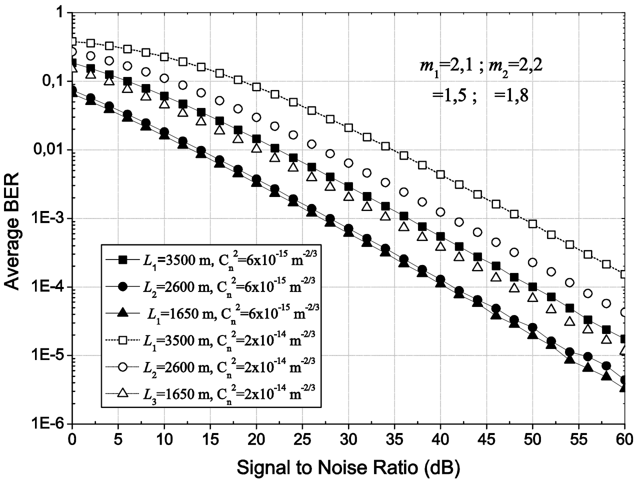



Fig. 4. Average BER for different values of propagation $L$ and different values of refraction index, for the considered set of turbulence channel parameters.

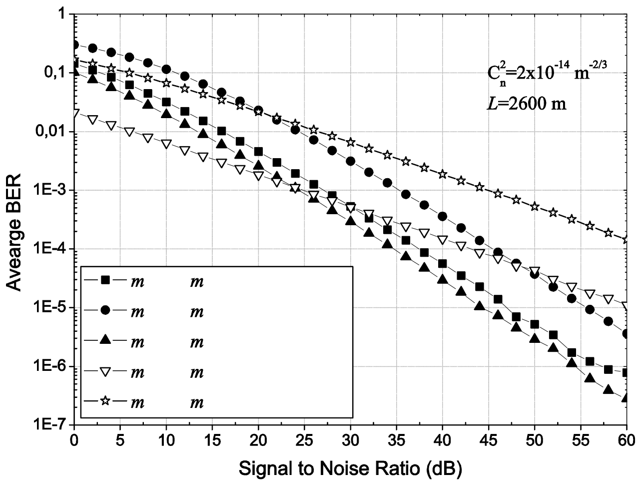



Fig. 5. Average BER for different values of turbulence shaping and severity parameters $\gamma_1$, $\gamma_2$, $m_1$, $m_2$.

In the Fig. 6 and the Fig. 7 are presented reconstructed images after transmission over FSO DGG turbulence channel within two analysed scenarios. In the both scenarios propagation distance was set to $L = 2600$ m, the wavelength $\lambda = 1500$ nm, refraction index of $C_n^2 = 2 \times 10^{-14}$ $m^{-2/3}$ and SNR = 40 dB. In the first scenario, with the presence of weak fading conditions (used values of turbulence channel parameters $\gamma_1 = 2.2$, $\gamma_2 = 2.2$, $m_1 = 2.0$, $m_2 = 2.0$, points on curve denoted with -■- in the Fig. 5) images have small degradation and are shown in the Fig. 6 as im1r1 and in the Fig. 7 as im2r1. In the second scenario, with the presence of strong fading conditions (used values of turbulence channel parameters are $\gamma_1 = 2.2$, $\gamma_2 = 1.1$, $m_1 = 2.0$, $m_2 = 2.0$, points on curve denoted with -☆- in the Fig. 5) images are more degraded and are shown in the Fig. 6 as im1r2 and in the Fig. 7 as im2r2.

(a)

(b)

Fig. 6. Reconstructed Image (im1) after transmission over FSO DGG fading channel with different parameter values: a) im1r1; b) im1r2.

Our goal was to determine theoretical BER values for some last mile FSO transmission realizations in such observed scenarios. In this way we have determined just lower boundary values of the quality of transmitted image, since by introducing the usage of some of well-known error correction code techniques (as explained i.e. in [21]), additional quality improvement can be achieved.

(a)

(b)

Fig. 7. Reconstructed Image (im2) after transmission over FSO DGG fading channel with different parameter values: a) im2r1; b) im2r2.

## IV. Conclusions

In this paper, we have investigated the BER performance of colour image FSO transmission over DGG turbulence channels. We have presented the obtained BER performance as the function of various FSO link parameters. It is shown that the increase of the parameter $C_n^2$ value causes an increase of the BER. Also it can be concluded that the decrease of parameter $\gamma_2$ value leads to the increase of the BER for all the observed values of SNR.

The analysis has been carried out for very general turbulence scenario, which can be reduced to many other ones. By applying the analysis presented in this work, FSO link designers can determine boundary values for achieving required BER values in the wide span of colour image last-mile transmission scenarios. Presented analysis could also serve as good starting point for FSO transmission analysis of the video signal over turbulence channels in corresponding last mile realizations.

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