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On the Block Error Rate of FSO Links with Diversity Over Mixture Gamma Turbulence Channels

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Abstract
Recently, wireless communications started incorporating free space optical (FSO) systems to a large extent due to their high bandwidth and the low installation and operational cost. However, their performance deteriorates significantly due the weather conditions and the atmospheric phenomena. A very significant issue is the atmospheric turbulence which causes the scintillation effect and results in fast power fluctuations at the receiver which can be modelled through the appropriate stochastic models. A recently presented, accurate and with relatively simple mathematical form is the Mixture Gamma distribution. In order to improve the system’s performance, various methods have been proposed and the receivers’ diversity has proven to be a very effective one. In this work, for first time to the best of our knowledge, the average block error rate (BLER) performance of a terrestrial FSO communication link with receivers’ diversity is estimated and new mathematical expressions are derived, for weak to strong turbulence channels with the Mixture Gamma distribution which emulate accurately the most of the well-known turbulence models. The derivation of the specific mathematical expressions is significant, especially for the modern FSO communication systems and networks with very high data rates, because if the BLER performance is known, the most efficient coding scheme can be chosen. Finally, using the new derived theoretical outcomes, the corresponding numerical results are presented for common FSO link parameters.

Key words:
Block Error Rate; Free Space Optical Communication Systems; SIMO links; Receivers’ Diversity; Atmospheric Turbulence; Mixture Gamma Model
1. Introduction

FSO systems have attracted research and commercial interest during the last few years due to the plenty of advantages they offer such as the very high data rate transmission and the relatively low installation and operational cost, [1]-[5]. Due to these advantages, FSO systems will be an inseparable part of the wireless communication systems of next generation, i.e. 5G/5G+, etc, [6]. Such communications systems are also used in underwater environment, [7]. Besides, the performance characteristics of the FSO communication links depend strongly on the channel state, i.e. the atmospheric conditions and the variations that prevail along the propagation path of the laser beam. An important factor which can degrades significantly their performance is the atmospheric turbulence which is responsible for the so-called scintillation effect and results in signal’s irradiance fluctuations at the receiver, [1]-[11].

Thus, various statistical models have been proposed and examined in order to model the receiver’s irradiance fluctuations. In this work, the recently presented mixture Gamma (MG) model is used, which has been proven to be an accurate approximation and given through a less complicated mathematical expressions comparing with the most of the distributions which are usually used in order to describe the influence of the atmospheric turbulence effect, [12]-[15].

The way that the turbulence reduces the performance, the reliability and the availability of the optical wireless communication systems has been studied through the bit error rate (BER), the outage probability (OP), the average and the outage channel capacity, etc, [16]-[21]. However, due to the very high data rates that the modern wireless communication systems and especially the FSO systems can achieve, [22], along with the broad use of coding schemes, [4], [5], [23], [24], the quantity which represents the rate of errors for a specific
block of bits, can describe much better the system's performance and additionally, can give more reliable and realistic information for its operation characteristics, [25]-[27].

Many techniques have been used in order to counterbalance the systems’ performance mitigation due to the atmospheric turbulence effect. One of them is the diversity and it has been proved that it can significantly improve the systems’ characteristics, [26]-[32]. In receiver diversity technique, multiple copies of the information signal are sent toward the receivers. The majority of the diversity schemes are realized either in space, in time or in wavelength, [26]-[37]. In spatial receivers’ diversity, the FSO system consists of one transmitter and multiple receivers in different places and thus, many copies of the information signal propagate through the atmospheric channel toward each receiver. This way, the system's error probability decreases, and it can be simulated as a single-input-multiple-output (SIMO) communication link with one transmitter and multiple receivers, [29], [36], [38], [39]. Furthermore, in time diversity schemes, the FSO systems consists of a one single transmitter and receiver and the multiple copies of the signal are sent in different time slots, [34], [37]. Moreover, when wavelength diversity is deployed, every copy of the signal can be transmitted using different wavelengths in multiple receivers that can detect only a specific frequency, [35]. Here, the receivers’ spatial diversity is assumed and is examined as a mitigating mechanism against the negative influence of the atmospheric turbulence effect. Thus, in this work, for first time, the performance and reliability of a SIMO FSO link with on-off-keying (OOK) modulation is studied by means of its average BLER performance. Specifically, the probability of having more than \( M \) erroneous bits in each specific block of \( N \) bits, is investigated, [25]. The specific performance information is necessary for choosing of the suitable coding scheme for the design of effective and reliable FSO links.

The remainder of this work is organized below as follows: in section 2, the FSO communication system and the channel model for spatial diversity is introduced while in
section 3, the average BLER is closely approximated. Next, in section 4, the numerical results are presented for various realistic parameter values of the system while the paper’s conclusions are summarized in section 5.

2. System Model

The SIMO FSO communication system under consideration deploys $K$ receivers’ spatial diversity. Moreover, it is assumed that an intensity modulation/direct detection (IM/DD) scheme is used and the laser beam propagates along a horizontal path through a turbulent channel with additive white Gaussian noise (AWGN). The channel is also considered to be memoryless, stationary and ergodic with independent and identically distributed intensity fluctuations. Due to the SIMO configuration, each propagation path causes different distortion at the information signal. Thus, the optical signal which arrives in each one of the $K$ receivers, is given as, [28], [29]:

$$r_l = s_l x + n = \eta_l x I_l + n_l, \quad l = 1, 2..., K$$

(1)

where $r_l$ is the optical signal which arrives at the $l$-th receiver, $s_l = \eta_l I_l$ is the instantaneous intensity gain, $\eta_l$ stands for the effective photo-current conversion ratio of the receiver, $I_l$ represents the normalized irradiance affected by each propagation path, $x$ is the modulated signal which is taking the binary values “0” or “1”, while $n_l$ is the AWGN with zero mean and variance $N_0/2$, [38].

In order to model the irradiance fluctuations due to atmospheric turbulence effect the MG distribution is used. The specific distribution is selected due to the fact that is a very accurate model to describe the signal’s variations while being expressed by a relatively less complicated mathematical expression, compared with other statistical models used for the
turbulence effect [12], [13]. Additionally, the specific distribution can emulate accurately most of the well-known models which are used to describe the irradiance’s variations due to the atmospheric turbulence effect. This choice results, as will be shown in Section 3, in compact mathematical expressions for the performance estimation of the FSO links which can be easily used for the design and implementation of the modern optical wireless communication systems.

The probability density function (PDF) of the MG distribution model, as a function of the irradiance \( I_i \), is given as, [12]:

\[
f_{I_i}(I_i) = \sum_{l=1}^{T} w_{i,l} f_{I_i}(I_i) = \sum_{l=1}^{T} a_{i,l} I_i^{b_{i,l}-1} \exp\left(-\zeta_{i,l} I_i\right), \quad l = 1, 2, \ldots, K
\]

where \( T \) is the number of the summation terms, \( f_{I_i}(x) = \xi_{i,j}^{-\alpha_i} x^{\alpha_i-1} e^{-\zeta_{i,j} x} / \Gamma(\alpha_i) \) is the PDF of a Gamma distribution and \( a_{i,l}, b_{i,l}, \zeta_{i,l} \), are the parameters of the \( i \)-th Gamma component, \( w_{i,l} = a_{i,l} \Gamma(b_{i,l}) \xi_{i,l}^{-\beta_i} \) while \( \sum_{i=1}^{K} w_i = 1 \) and \( \Gamma(.) \) represents the Gamma function, [13], [40].

The MG model can approximate accurately some of the well-known models used for the description of the turbulence-induced irradiance fluctuations by setting the values in the parameters \( a_{i,l}, b_{i,l} \) and \( \zeta_{i,l} \). More precisely the Gamma-Gamma distribution with PDF [15]:

\[
f_{I_i}(I_i) = \frac{2(\alpha_i, \beta_i, I_i)}{\Gamma(\alpha_i) \Gamma(\beta_i) I_i} K_{\alpha_i, \beta_i, I_i} \left(2\sqrt{\alpha_i \beta_i I_i}\right),
\]

can be approximated by selecting in the MG PDF the following parameter values, [13], [40]:
\[ a_{i,j} = \frac{\theta_{i,j}}{\sum_{j=1}^{T} \theta_{i,j} \Gamma(b_{i,j}) \varphi^{b_{i,j}}}, \quad b_{i,j} = \alpha_i \varphi_{i,j} = \frac{\alpha_i \beta_i}{\theta_{i,j}}, \quad \theta_{i,j} = \frac{(\alpha_i \beta_i)^{\theta_i} w_i f_{i,j}^{-\alpha_i+\beta_i-1}}{\Gamma(\alpha_i) \Gamma(\beta_i)}, \quad (4) \]

where \( \alpha_i \) and \( \beta_i \) are the well-known parameters of Gamma-Gamma distribution that depend on the link’s characteristics, [15].

For the case of the negative exponential distribution with the following PDF, [14]:

\[ f_{l_i}(I_i) = \exp(-I_i), \quad (5) \]

the corresponding parameter values can be extracted as, [40]:

\[ a_{i,j} = \theta_{i,j} \left[ \sum_{j=1}^{T} \theta_{i,j} \Gamma(b_{i,j}) \varphi^{b_{i,j}} \right]^{-1}, \quad b_{i,j} = 1, \quad \varphi_{i,j} = 1, \quad \theta_{i,j} = 1 \quad (6) \]

By expressing the instantaneous and the expected signal to noise ratio (SNR) in the \( l \)-th receiver as, \( \gamma_i = (\eta I_i)/N_0 \) and \( \xi_i = (\eta E[I_i])^2/N_0 \), [29], respectively, with \( E[I] \) being the irradiance’s expected value and substituting into Eq. (2), the following PDF for the MG distribution, as a function of \( \gamma_i \), is obtained, [12], [13]:

\[ f_{\gamma_i}(\gamma_i) = \sum_{l=1}^{T} \frac{a_{l,i}}{2\sqrt{\xi_l}} \left( \frac{\gamma_i}{\xi_l} \right)^{b_{l,i}-3/2} \exp\left(-\frac{\xi_{l,i}}{\xi_l} \sqrt{\frac{\gamma_i}{\xi_l}}\right), \quad l = 1, 2, \ldots K \quad (7) \]

where, without loss of generality, the \( E[I] \) value has been assumed as equal to unity, [29]. Then, using the appropriate values for parameters \( a_{l,i}, b_{l,i}, \varphi_{l,i} \), many of the well-known
statistical distributions for the irradiance fluctuations study, due to the atmospheric turbulence effect, can be modeled, [12], [13].

In this work, the GG and the negative exponential (NE) distributions have been chosen, because it is proved that they represent very accurate models for the cases of weak to strong and saturate turbulence conditions, respectively, [34], [41]-[46]. Additionally, by using the MG distribution, the mathematical expressions of the average BLER results which will be obtained will be much less complicated than those with the original GG and NE PDFs. Thus, the use of the MG model results in very accurate outcomes along with relatively compact mathematical expressions for the FSO performance estimation.

3. Average Block Error Rate Estimation

Average BLER is a very significant and reliable quantity for the performance estimation of terrestrial FSO links. More specifically, the optical wireless communication systems support very high data rates transmission, i.e. of order of Gbps, while the coherence time of the atmospheric channel due to the atmospheric turbulence effect is of order of milliseconds, [22]. Thus, the channel’s characteristics remain practically invariant for a large number of information bits and consequently, the probability of having more than \( M \)-bit errors in a block of \( N \)-bits, which is estimated through the average BLER, represents an important quantity for the link’s reliability while can help at the choice of coding scheme which could fit better in each FSO communication link. More specifically, \( M \) represents the number of erroneous bits the block can afford, in order to be considered as correct. Thus, the probability of having more than \( M \) error bits in a block of \( N \), so that the block is characterized as faulty, is given as, [25], [26]:
where $p$ stands for the probability of receiving an error bit in the case of OOK modulation. In the case of $K$ receivers’ diversity scheme and by assuming maximum ratio combining (MRC) scheme, the probability $p$ of incorrect detection for the OOK scheme, is given as, [29]:

$$p = Q\left(\sqrt{\sum_{l=1}^{K} \gamma_l}\right)$$  \hspace{1cm} (9)$$

Next, by averaging the expression (8) of the instantaneous BLER of the optical communication system, the following multiple integral for the estimation of the average BLER, i.e. ABLER, is obtained, [25]:

$$ABLER = \int_{\tilde{\gamma}} P(M, N; \tilde{\gamma}) f_{\tilde{\gamma}}(\tilde{\gamma}) d\tilde{\gamma}$$  \hspace{1cm} (10)$$

where $\tilde{\gamma} = (\gamma_1, \gamma_2, ..., \gamma_K)$ is the $K$-components vector signal which arrives at the receivers of the SIMO FSO system with spatial diversity, [25], [36].

Next, by substituting (8), (9) into (10), the average BLER of the SIMO FSO link with OOK, is given as:

$$ABLER = \int_{\tilde{\gamma}} \sum_{m=M+1}^{N} \binom{N}{m} p^m (1-p)^{N-m} \left[1 - Q\left(\sqrt{\sum_{l=1}^{K} \gamma_l}\right)\right]^{N-m} f_{\tilde{\gamma}}(\tilde{\gamma}) d\tilde{\gamma}$$  \hspace{1cm} (11)$$
In order to solve the above $K$-fold integral of (11), $Q$-function is approximated with the following fairly accurate expression, which is proposed in [47]:

$$Q(x) \approx \frac{1}{12} \left[ \exp \left( -\frac{x^2}{2} \right) + 3 \exp \left( -\frac{2x^2}{3} \right) \right]$$  \hspace{1cm} (12)

Furthermore, by using the binomial expansion and the multinomial formulae, the integral of (12) is taking the following form:

$$ABLER \approx \int \sum_{m=M+1}^{N} \binom{N}{m} \sum_{j=0}^{N-m} \binom{N-m}{j} (-1)^j \sum_{r=0}^{m+j} \binom{m+j}{r} \times$$

$$\left[ \frac{1}{12} \prod_{l=1}^{K} \exp \left( -\frac{\gamma_l}{4} \right) \right]^{m+j-r} \left[ \frac{1}{4} \prod_{l=1}^{K} \exp \left( -\frac{\gamma_l}{3} \right) \right]^r f_{\tilde{\gamma}}(\tilde{\gamma}) d\tilde{\gamma}$$  \hspace{1cm} (13)

and since $\gamma_l$ are independent, by grouping terms with index $l$, the $K$-fold integral of (13) is transformed into a product of $K$ one-dimensional integrals, [48], of the form:

$$ABLER \approx \prod_{l=1}^{K} \int \sum_{m=M+1}^{N} \binom{N}{m} \sum_{j=0}^{N-m} \binom{N-m}{j} (-1)^j \frac{(m+j-r)}{12^{m+j-r} 4^r} \times$$

$$\prod_{r=0}^{m+j} \binom{m+j}{r} \exp \left( -\frac{\gamma_l(3m+3j+r)}{12} \right) f_{\tilde{\gamma_l}}(\gamma_l) d\gamma_l$$  \hspace{1cm} (14)

Next, by substituting the PDF of (4) into (14) the final integral expression for the ABLER estimation for SIMO FSO link over MG turbulence channels is obtained. More specifically, from (2), (4) and (14), the following expression is derived:
In order to solve the integral products of (15), the exponential and the Bessel functions are substituted by the proper Meijer-G functions, [49]. Next, by integrating using [50], the average BLER for the MG OOK FSO communication system with receivers’ diversity, is given as:

\[
\text{ABLER} = \prod_{l=1}^{K} \left[ \sum_{m=M+1}^{N} \sum_{j=0}^{N-m} \binom{N}{m} \binom{N-m}{j} (-1)^j 12^{m+j-r} 4^r \times \right.
\]
\[
\times \sum_{r=0}^{m+j} \binom{m+j}{r} \sum_{l=1}^{\infty} \exp \left( -\frac{\gamma_l (3m+3j+r)}{12} \right) \times \exp \left( -\gamma_l \sqrt{\frac{\zeta_{l,r}}{\gamma_l}} \right) d\gamma_l
\]

(15)

with \( D_n(z) \) being the parabolic cylinder function which is given as, [49]:

\[
D_n(z) = 2^{n/2+1/4} z^{-1/2} W_{n/2+1/4,-1/4} \left( \frac{z^2}{2} \right)
\]

(17)

where \( W_n(.) \) is the Whittaker function, [46].
Thus, by substituting (17) into (16), the average BLER of an FSO link with receivers’
diversity over MG turbulence channels is given as:

\[
\text{ABLER} \approx \prod_{i=1}^{K} \left[ \sum_{m=d+1}^{N} \left( \sum_{j=0}^{N-m} \left( \sum_{r=0}^{m+j} \left( \begin{array}{c}
N-m \\
j \\
r
\end{array} \right) \right) \right) \right] \times
\]

\[
\times \sum_{i=1}^{T} \frac{2a_{i,j}(-1)^j}{\xi_{ij}^{b_{ij}-1/2}} \left( \frac{12^{m_j}}{4^{r_j}} \right) \Gamma \left( 2b_{ij} - 1 \right) \left( \frac{3m_j + 3j + r_j}{12} \right)^{b_{ij} - 1/2}
\]

\[
\times \exp \left( \frac{\zeta_{ij}^2}{8\xi_{ij}^2 (3m_j + 3j + r_j)} \right) 2^{-b_{ij}} \left( \frac{\zeta_{ij} \sqrt{12}}{\sqrt{\xi_{ij} (3m_j + 3j + r_j)}} \right)^{-1/2}
\]

\[
\times W_{b_{ij} - 1/4, -1/4} \left( \frac{\zeta_{ij}^2}{4\xi_{ij}^2 (3m_j + 3j + r_j)} \right)
\]

In order to investigate the accuracy of the expression (18) using the approximation (12),
the average BLER of the specific FSO link has also been estimated using a more com pact,
but more accurate, approximation for the Q-function, [25], and is given as:

\[
Q(x) = \frac{1}{24} \left[ 5 \exp \left( -2x^2 \right) + 4 \exp \left( -\frac{11x^2}{20} \right) + \exp \left( -\frac{x^2}{2} \right) \right]
\]

Then, by substituting (19) into (11), and following a similar procedure as above, the
following mathematical expression for the estimation of the average BLER of FSO links over
MG turbulence channels with receivers’ diversity, is derived:
It can be seen that the expression (20) is much more complicated than (18) while, due to the higher accuracy of (19) compared with (12), the expression (20) gives more accurate results than (18). However, as it will be shown by the corresponding numerical results in the next section, the outcomes of (18) are very close to those of (20) for the most of the realistic cases and taking into account the more compact form of (18), we conclude that both expressions, i.e. (18) and (20), can be used for the system’s performance estimation, depending on the accuracy, and thus for the designing and implementation of efficient SIMO FSO links.

4. Numerical Results

The above derived mathematical expressions, (18) and (20), can be directly used for the estimation of the average BLER performance of the SIMO FSO system over MG atmospheric turbulence channels. Additionally, the better accuracy which (20) provides, verifies the outcomes of the much more compact expression of (18). All results have also been verified using the Monte Carlo (MC) simulation method.
In order to estimate the average BLER performance for realistic cases, here we assume that the bit blocks consist of $N=3$, $4$ or $5$ bits and a block is erroneous in case more that $M$ bits per bit block are faulty, using various values for $M$. In order to lower the complexity of (15) and (17), small values for parameters $N$ and $M$ were selected. The pairs $(N,M)$ are indicated in the legend of every figure. In order to emulate the GG and NE with the MG distribution, the parameters $a$, $b$, $\zeta$ will take specific values,[13], [40]. More specifically, the parameters of the MG distribution for the case of NE are fixed at $(a,b,\zeta)=(1,1,1)$ and $T=1$, [40]. However, for the GG model, we consider $T=3$ while the other parameters for moderate turbulence take the values: $\omega=(1.57,18.49,0.052)$, $b_i=(2,2,2)$, $\zeta_i=(23.81,4.35,1.59)$ with $i=1...T$. For the spatial diversity scheme, in Fig. 3 we assume for simplicity that, the expected electrical SNR is the same for all the $K$ receivers, i.e. $\xi_1=\xi_2=...=\xi_K=\xi$, but results for different SNR for every receiver are also provided for comparison in Figs 4 and 6. However, it should be emphasized here that using the above derived expressions (15) and (17), the average
BLER performance of any specific SIMO FSO link can be easily evaluated. Simulation results will also be provided by applying MC technique in (12). It has to be noticed that in case of SIMO, i.e. \( K>1 \), Eq. (12) will give a product of \( K \) different integrals that will be solved separately using MC.

**Fig. 2:** Average BLER as a function of expected electrical SNR, \( \xi \), for saturated turbulence for a SISO FSO communication system using Eq. (20).

In Figs 1 and 2, the average BLER results are presented for the case where the MG distribution emulates the NE model and by assuming a single input single output (SISO) system, i.e. without spatial diversity, using Eqs (18) and (20), respectively. In Fig. 3 the receivers’ diversity scheme is studied and results for \( K=3 \) are presented for equal SNR in every receiver, while in Fig.4 we present the corresponding results for different SNR in each receiver, i.e. \( \xi_1, \xi_2=0.9\xi_1 \) and \( \xi_3=0.8\xi_1 \).
By comparing Fig.1 and 2, both average BLER expressions give nearly identical results, especially for low SNR values. More precisely, for SNR equal to 15dB the difference between the results of Eq. (18) comparing with the corresponding ones of (20), varies between 2% and 9% while for 40dB SNR value, the corresponding difference lies from 5% to 14%, for \((N,M)=(3,2)\) and \((N,M)=(5,2)\), respectively. Thus, taking into account that the expression (20) has been obtained using a more accurate but more complicated approximation for the Q-function than Eq. (18), and the obtained results from both equations are very close to each other, we conclude that the expression (18) could be used for accurate enough BLER performance evaluation and thus, for system’s reliable designing.
Thus, it can be seen that, as the number of accepted erroneous bits, $M$, in a certain number of block bits, $N$, increases, the BLER decreases as expected and explained in Section 3. Furthermore, the use of diversity technique with 3 receivers significantly increases the reliability of the SIMO FSO system as the BLER decreases more than five orders of magnitude. It is also clear that as the number of bits $N$ increases, the acceptable number of erroneous bits $M$ also increases in order to maintain the performance of the system.
Fig. 5: Average BLER as a function of the expected electrical SNR, $\xi$, for the case of moderate atmospheric turbulence for a SISO wireless optical communication system.

Fig. 6: Average BLER as a function of the expected electrical SNR, $\xi$, for the case of moderate atmospheric turbulence for a SIMO wireless optical communication system with receivers’ in “Case A” with different SNR in every receiver and “Case B” with equal SNR.
In Figures 5 and 6, the corresponding results for the case where the MG distribution emulates the GG model in case of moderate turbulence strength turbulence conditions in a SISO and SIMO system are presented. More specifically, in Figure 6, where the SIMO results are shown, using the result (15) in case the SNR is different for every receiver, i.e., “Case A”, and in case the SNR is equal, i.e., “Case B”. Thus, as in the case of NE, the average BLER of the system decreases as the number of the correct bits $M$ increases in a block of $N$ bits. Finally, the diversity technique clearly enhances the performance of the system e.g., even for low values of $\xi$, the FSO link with diversity may achieve an average BLER lower than $10^{-11}$.

5. Conclusions

In this work, we studied the average BLER performance of a SIMO FSO communication system with spatial diversity over weak to strong and saturate atmospheric turbulence channels modelled with the MG distribution. The use of the specific distribution model, due to its relatively less complicated PDF expression, results in a compact and useful mathematical expression for the average BLER estimation. The specific quantity, which has not been estimated previously for SIMO FSO links, is very significant for the modern ultra-fast FSO links which achieve very high data rates because it can help with the choice of the more efficient coding scheme which should be used for each specific SIMO optical wireless link. Additionally, in order to examine the accuracy of the derived mathematical expressions which have been obtained, their outcomes have been compared for various realistic cases and the corresponding conclusions have been extracted. Furthermore, the accuracy of the theoretical outcomes of this work has been verified with the corresponding Monte Carlo simulations.
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