Spatial Diversity For FSO Communication Systems Over Atmospheric Turbulence Channels

Mohamed Abaza*, Raed Mesleh*, Ali Mansour†, and El-Hadi M. Aggoune*
*Sensor Networks and Cellular System (SNCS) Research Center, University of Tabuk, 71491 Tabuk, Saudi Arabia
{mabaza.sncs, rmesleh.sncs, haggoune.sncs}@ut.edu.sa
†Lab STICC, ENSTA Bretagne, 2 Rue François Verny, 29806 Brest Cedex , France, Email: mansour@ieee.org

***Abstract*—This paper investigates the bit error rate (BER) performance of spatial diversity free-space optical (FSO) communication systems using on-off keying modulation. The study considers correlated log-normal FSO channels as well as path losses due to weather effects using intensity modulation and direct detection schemes. An approximated moment generating functions (MGF) for the joint probability density function of correlated log-normal channels are considered. Using MGF approximation, BER expressions for repetition codes (RCs) and orthogonal space time block codes (OSTBCs) in correlated log-normal channels are derived. Results show that RCs outperform OSTBCs in correlated channel conditions. In addition, the effect of different weather conditions (e.g., haze, rain and fog) on the BER performance of the FSO links are studied. Monte Carlo simulation results are further provided to demonstrate the validity of the proposed mathematical analysis.**

***Index Terms*—Free-space optical communications; atmospheric turbulence; spatial diversity; orthogonal space time block codes; repetition codes.**

I. Introduction

Free-space optical (FSO) communication has gained significant interest in last-mile terrestrial applications as it is cheap, license-free and it can achieve high data rate wireless communication. However, FSO systems still face a number of design challenges, including severe attenuation under different weather conditions (e.g., haze, rain and fog) and performance degradation due to atmospheric turbulence induced fading [1, 2].

Radio frequency (RF) and FSO are affected differently by atmospheric and weather effects. FSO links suffer from high attenuation in the presence of fog but are less affected by the rain. In contrast, fog has practically no effect on RF systems, but the rain significantly increases link attenuation. Atmospheric turbulences due to changing temperature or pressure result in non-homogeneous fluctuations of local refractive indexes. These turbulences are the main reason behind the fading in FSO links. While in RF links, the fading is due to the multipath propagation [2, 3].

In the last two decades, many statistical models have been proposed to describe the atmospheric turbulence strength in FSO. It has been shown that for weak turbulence, the distribution of received intensities is close to a log-normal distribution, while in strong turbulence conditions; the gamma-gamma distribution can be used to model both small-scale and large-scale turbulences. The log-normal and the gamma-gamma distributions have good match between theoretical and experimental data [2].

Spatial diversity is considered as a promising solution to combat atmospheric turbulences. By using multiple apertures at the transmitter and/or the receiver sides, spatial diversity has the potential to mitigate atmospheric turbulence effects, enhances the performance of the FSO links and overcomes the limitations on the transmit optical power. Also, the possibility for laser beam blockage by obstacles (e.g., birds or moving vehicles) is further reduced and longer distances can be covered through harsh weather conditions [4–8].

Two spatial diversity techniques are generally considered for FSO systems. Namely, repetition codes (RCs) and orthogonal space time block codes (OSTBCs) [9]. In RCs system, the same signal is transmitted simultaneously from the available transmitters. The advantages of such transmission technique are limited to FSO wireless systems using a heterodyne (coherent) reception. A heterodyne reception offers distinct advantages, as the background noise rejection and the mitigation of atmospheric turbulences. However, this kind of receiver is not preferred in FSO systems due to its high cost and complexity. Alternatively, intensity modulation with direct detection (IM/DD) [9, 10] are more preferred transmission/reception methods.

Conventional OSTBCs, as used in RF systems, should be modified to deal with IM/DD techniques because the output of the transmitter must be unipolar [11, 12]. To achieve this, the negative part of a modulated signal is represented by the 1's complement (i.e., bitwiseNot) of a positive signal [11]. However, it has been shown in [9] that RCs outperform their counterpart OSTBCs using IM/DD in uncorrelated log-normal channels. Yet, coherent and differential OSTBCs FSO systems are shown to outperform their counterpart RCs systems at the expense of laborious receivers [13].

Uncorrelated log-normal channels require that the distances among transmitters must exceed the fading correlation length. However, this might be unattainable in practical systems as the available space for transmitters may not be sufficient to achieve this requirement [14]. Therefore and in this paper, BER expressions for IM/DD FSO system using RCs and OSTBCs in the presence of both correlated log-normal channel and path loss attenuation due to weather effects are derived. The

978-1-4799-3083-8/14/$31.00 ©2014IEEE

derivation is based on the approximated MGF for correlated log-normal channels, which is derived in [15].

The remainder of this paper is organized as follows: FSO spatial diversity model is presented in Section II. In Section III, performance analysis are discussed. Numerical results and discussions are given in Section IV. Finally, conclusions are summarized in Section V.

II. System Model

A synoptic diagram of the considered system model is depicted in Fig. 1. The system considers N_t transmitters and one receiver. Source bits are modulated using on-off keying (OOK) pulsed modulation and encoded by a multiple-input single-output (MISO) encoder. The encoder considers two techniques for transmission, OSTBCs and RCs. In RCs system, the same signal is transmitted simultaneously from the available transmitters. While in OSTBCs, full rate real orthogonal matrices, $\mathbf{G}$, for $N_t \leq 8$, are considered [16]. In [16], a linear transformation of $\mathbf{G}$ matrix to OOK matrix, $\mathbf{S}$, through $\mathbf{S} = \frac{\mathbf{U}+\mathbf{G}}{2}$ is proposed, where $\mathbf{U}$ denotes a unit matrix with the same size as $\mathbf{G}$. The encoded real symbols modulate

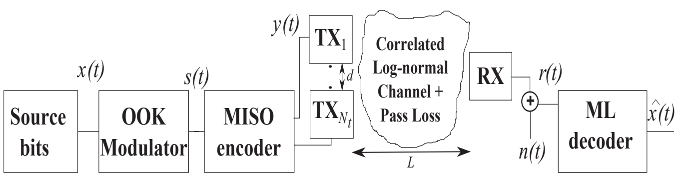

Fig. 1. Synoptic diagram of the proposed model.

the synchronized laser diodes. The transmitted light propagates over correlated log-normal channel and suffers from path loss due to weather effects and an additive white Gaussian noise (AWGN) at the receiver input. As such, the received signal is given by

$$r(t) = s(t)\eta \sum_{i=1}^{N_t} I_i + n(t), \tag{1}$$

where $s(t)$ is the transmitted information symbol, η is the optical to electrical conversion coefficient, $n(t)$ is an AWGN at the receiver input (the noise is mainly due to shot noise which dominates over other noise sources such as thermal, signal-dependent or dark noises [9]) and I_i denotes the received signal light intensity from the i^{th} transmitter to the receiver after channel effect. According to [1, 17], it can be evaluated as follows:

$$I_i = \beta \; I_o \; h_i, \tag{2}$$

with I_o being the received signal light intensity without considering the channel effect, $h_i = e^{(2X_i)}$ is the channel irradiance from transmitter i to the receiver with X_i being modeled as spatially correlated identically distributed Gaussian random variable with mean μ, standard deviation σ and variance σ^2.

The path loss, in dB, is modeled as [1]

$$\beta = -\alpha L, \tag{3}$$

where α is the weather-dependent attenuation coefficient (in dB/km) and L is the link distance.

The values of α for different weather conditions are provided in Table I [3].

TABLE I
WEATHER ATTENUATION COEFFICIENT OF FSO [3]

Weather conditions	α[dB/km]
Clear air	0.43
Haze	4.2
Moderate rain (12.5 mm/h)	5.8
Heavy rain (25 mm/h)	9.2
Light fog	20
Moderate fog	42.2
Heavy fog	125

Hence, h_i is a log-normal random variable (RV) with probability density functions (pdf) given by [18]

$$f(h) = \frac{1}{h\sqrt{8\pi\sigma^2}} \times \exp\left(-\frac{(\ln(h) - 2\mu)^2}{8\sigma^2}\right). \tag{4}$$

To ensure that the fading channel does not attenuate or amplify the average power, the fading coefficients are normalized as $\mathbf{E}[h_i] = e^{2(\mu+\sigma^2)} = 1$.

The spatial covariance matrix $\mathbf{\Gamma}$ coefficients, modeling the spatial correlation among transmitters, are given by [17]

$$\Gamma_{ij} = \sigma^2 \times \rho^{|i-j|}, \tag{5}$$

where $|.|$ stands for the absolute value, ($\rho \leq 1$) is the correlation coefficient and i and j are the row and the column indices of the covariance matrix coefficients, respectively. According to [14], ρ is a function of the separation distance d among transmitters,

$$\rho = \exp\left(-\frac{d}{d_o}\right), \tag{6}$$

where the correlation length $d_o \approx \sqrt{\lambda L}$ with λ being the wavelength. This correlation model is called the exponential model [19] and corresponds to the scenario of a multichannel transmission from linearly equi-spaced transmitters. From (6), the correlation of combined signals decays by increasing the spacing between the transmitters.

At the receiver side, maximum-likelihood (ML) decoder is considered.

III. Performance Analysis

A. Orthogonal Space Time Block Codes (OSTBCs)

The pdf of the instantaneous signal to noise ratio (SNR) γ_i, $1 \leq i \leq N_t$, of correlated jointly log-normal channel under atmospheric loss effect can be calculated as [1, 18]

$$f(\gamma_1, \cdots, \gamma_{N_t}) = \frac{\exp\left(-\frac{1}{32}\; Z\; (\mathbf{\Gamma})^{-1} Z^T\right)}{4^{N_t}\sqrt{(2\pi)^{N_t}(\det[\mathbf{\Gamma}])}\Pi_{i=1}^{N_t}\gamma_i}, \tag{7}$$

where $Z = \left[\ln\left(\frac{\gamma_1}{\beta^2\overline{\gamma_1}}\right), \cdots, \ln\left(\frac{\gamma_{N_t}}{\beta^2\overline{\gamma_{N_t}}}\right)\right] - 4\mu$, $\overline{\gamma_i}$ is the average SNR, $(\cdot)^{-1}$ is the inverse of a matrix, $(\cdot)^T$ is the transpose of a matrix and det is the determinant of a matrix.

The instantaneous SNR γ_i in (7) is given by [5],

$$\gamma_i = \frac{(\eta I_i)^2}{N_o}. \tag{8}$$

The conditional BER for FSO system using OSTBCs can be calculated as [1, 9]

$$P(e|h) = Q\left(\sqrt{\frac{E_b\ \beta^2}{2N_o}\sum_{i=1}^{N_t} h_i^2}\right) \tag{9}$$

with E_b being the average electrical energy of the transmitted pulse at each transmitter given by [9]

$$E_b = \left(\frac{\eta I_o}{N_t}\right)^2. \tag{10}$$

The factor N_t is included in (10) to ensure that the total power of the considered MISO system is similar to the power of the benchmark single-input single-output (SISO) link.

The alternative form of the Gaussian-Q function is [20]

$$\begin{aligned} Q(y) &\triangleq \frac{1}{\sqrt{2\pi}}\int_y^\infty \exp\left(-\frac{x^2}{2}\right) dx \\ &= \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \exp\left(-\frac{y^2}{2\sin^2\theta}\right) d\theta. \end{aligned} \tag{11}$$

Substituting (10) into (9) and using (2) yields

$$P(e|h) = Q\left(\sqrt{\frac{\eta^2}{2N_o(N_t)^2}\sum_{i=1}^{N_t} I_i^2}\right). \tag{12}$$

Using (8), the conditional BER with respect to the SNR becomes

$$P(e|h) = Q\left(\sqrt{\frac{\sum_{i=1}^{N_t}\gamma_i}{2(N_t)^2}}\right). \tag{13}$$

Using the pdf of the instantaneous SNR γ_i in (7), the average bit error probability of OSTBCs is given by

$$\begin{aligned} \mathrm{BER} = \int_0^\infty \cdots \int_0^\infty Q\left(\sqrt{\frac{\sum_{i=1}^{N_t}\gamma_i}{2(N_t)^2}}\right) \times \\ f(\gamma_1, \cdots, \gamma_{N_t})\ d\gamma_1 \cdots d\gamma_{N_t}. \end{aligned} \tag{14}$$

According to [21], the MGF is defined by

$$\begin{aligned} \Psi(s) = \int_0^\infty \cdots \int_0^\infty\ f(\gamma_1, \cdots, \gamma_{N_t}) \times \\ \exp\left[-s\sum_{i=1}^{N_t}\gamma_i\right] d\gamma_1 \cdots d\gamma_{N_t}. \end{aligned} \tag{15}$$

With the use of (7) and after few algebraic manipulations, the pdf of instantaneous branch SNR for the given branch i ,γ_i, is

$$f(\gamma_i) = \frac{1}{\sqrt{32\pi\sigma^2}\gamma_i}\exp\left[-\frac{\left(\ln\left(\frac{\gamma_i}{\beta^2\bar{\gamma}_i}\right)+4\sigma^2\right)^2}{32\sigma^2}\right] \tag{16}$$

The MGF of the RV γ_i is then given by

$$\begin{aligned} \Psi(s) = \int_0^\infty \exp(-s\gamma_i)\frac{1}{\sqrt{32\pi\sigma^2}\gamma_i} \\ \times \exp\left[-\frac{\left(\ln\left(\frac{\gamma_i}{\beta^2\bar{\gamma}_i}\right)+4\sigma^2\right)^2}{32\sigma^2}\right] d\gamma_i. \end{aligned} \tag{17}$$

Making the change of variable $x = \frac{\left(\ln\left(\frac{\gamma_i}{\beta^2\bar{\gamma}_i}\right)+4\sigma^2\right)}{\sqrt{32\sigma^2}}$ yields

$$\begin{aligned} \Psi(s) = \frac{1}{\sqrt{\pi}}\int_{-\infty}^\infty \exp(-x^2) \\ \times \exp\left(-s\beta^2\bar{\gamma}_i\exp(\sqrt{32\sigma^2}x - 4\sigma^2)\right) dx. \end{aligned} \tag{18}$$

Using Hermite polynomial approximation gives [22, page 924]

$$\int_{-\infty}^\infty \exp(-x^2)g(x)dx \approx \sum_{i=1}^N w_i g(x_i), \tag{19}$$

where w_i and x_i are the weights and the roots of the Hermite polynomial, respectively.

Applying (19) on (18) yields

$$\Psi(s) \approx \frac{1}{\sqrt{\pi}}\sum_{i=1}^N w_i \exp\left(-s\beta^2\bar{\gamma}_i\exp(\sqrt{32\sigma^2}x_i - 4\sigma^2\right) \tag{20}$$

Using (20), (7) and following similar approach as in [15], the general form of the MGF in correlated log-normal channel under atmospheric loss effect is given by

$$\begin{aligned} \Psi(s) \approx \sum_{n_1=1}^N \cdots \sum_{n_{N_t}=1}^N \left[\prod_{i=1}^{N_t}\frac{w_{n_i}}{\sqrt{\pi}}\right] \\ \times \exp\left(-s\sum_{i=1}^{N_t}\beta^2\bar{\gamma}_i\left[\exp\left(\sqrt{32}\sum_{j=1}^{N_t}c'_{ij}x_{n_j} - 4\sigma^2\right)\right]\right), \end{aligned} \tag{21}$$

with N being the order of approximation of the Hermite polynomial. The values of w_{n_i} and x_{nj} of the N^{th} order Hermite polynomial are tabulated in [22, Table 25.10] and c'_{kj} is the $(k, j)^{\mathrm{th}}$ coefficient of $\mathbf{\Gamma}_{\mathrm{sq}} = \mathbf{\Gamma}^{1/2}$.

Using the definition of the Q-function in (11) on (14) gives

$$\begin{aligned} \mathrm{BER} = \frac{1}{\pi}\int_0^\infty \cdots \int_0^\infty \int_0^{\frac{\pi}{2}} \exp\left(-\frac{\sum_{i=1}^{N_t}\gamma_i}{4N_t^2\sin^2\theta}\right) \times \\ f(\gamma_1, \cdots, \gamma_{N_t})\ d\theta\ d\gamma_1 \cdots d\gamma_{N_t}. \end{aligned} \tag{22}$$

The BER in (22) can be written using the MGF approach in (15) as

$$\mathrm{BER} = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \Psi\left(\frac{1}{4\mathrm{N_t^2}\sin^2\theta}\right) \mathrm{d}\theta. \tag{23}$$

Using (21) and assuming that all the average SNR from the transmitters are equal, i.e., $\bar{\gamma}_i = \bar{\gamma}$, $\forall i = 1, \cdots, N_t$, an approximate novel expression of the BER of OSTBCs over correlated log-normal channel under atmospheric loss effect is derived as

$$\mathrm{BER} \approx \sum_{n_1=1}^{N} \cdots \sum_{n_{N_t}=1}^{N} \left[\prod_{i=1}^{N_t} \frac{w_{n_i}}{\sqrt{\pi}} \right] \times Q\left(\sqrt{\frac{\beta^2 \bar{\gamma}}{2N_t^2} \sum_{i=1}^{N_t} \left[\exp\left(\sqrt{32} \sum_{j=1}^{N_t} c_{ij}' x_{n_j} - 4\sigma^2 \right) \right]} \right). \tag{24}$$

B. Repetition Codes (RCs)

The conditional BER of FSO system using RCs can be obtained as [1, 9]

$$P(e|h) = Q\left(\sqrt{\frac{E_b\ \beta^2}{2N_o}} \sum_{i=1}^{N_t} h_i \right). \tag{25}$$

Using the alternative definition of the Q-function in (11), the BER of RCs system over correlated log-normal channel under atmospheric loss effect is given by

$$\mathrm{BER} = \frac{1}{\pi} \int_0^{\infty} \cdots \int_0^{\infty} \int_0^{\frac{\pi}{2}} \exp\left(-\frac{\left(\sum_{i=1}^{N_t} \sqrt{\gamma_i} \right)^2}{4N_t^2 \sin^2\theta} \right) \times f(\gamma_1, \cdots, \gamma_{N_t})\ d\theta\ d\gamma_1 \cdots d\gamma_{N_t}. \tag{26}$$

Please note that the MGF approach cannot be used to represent (26), since it is directly proportional to $(\sqrt{\gamma_i}\,)^2$. However, under the condition that $\sigma^2 \ll 1$, the following approximation can be used

$$I_1 = \left(\sum_{i=1}^{N_t} \sqrt{\gamma_i} \right)^2 \approx I_2 = N_t \sum_{i=1}^{N_t} \gamma_i. \tag{27}$$

Monte Carlo simulation results with 10^5 samples are conducted to verify the validity of the proposed approximation in (27). The relative estimation error percent, $\xi = 100 \times \left(\frac{I_1 - I_2}{I_1} \right) < 6\%$, is calculated for different σ values. The results are shown in Table II. Results clearly demonstrate that the proposed approximation is valid and leads to a negligible error ($< 6\%$) with practical σ values.

TABLE II
ERROR DUE TO APPROXIMATION

σ	ρ	$\xi(\%)$
0.1	0.5	0.4
0.1	0.25	0.7
0.3	0.5	4
0.3	0.25	5.6

Hence, substitute (27) in (26) and using (15) yields

$$\mathrm{BER} \approx \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \Psi\left(\frac{1}{4\mathrm{N_t} \sin^2\theta} \right) \mathrm{d}\theta \tag{28}$$

From (21) and (28), an approximate expression for the BER of RCs systems over correlated log-normal channels under atmospheric loss effect is derived as

$$\mathrm{BER} \approx \sum_{n_1=1}^{N} \cdots \sum_{n_{N_t}=1}^{N} \left[\prod_{i=1}^{N_t} \frac{w_{n_i}}{\sqrt{\pi}} \right] \times Q\left(\sqrt{\frac{\beta^2 \bar{\gamma}}{2N_t} \sum_{i=1}^{N_t} \left[\exp\left(\sqrt{32} \sum_{j=1}^{N_t} c_{ij}' x_{n_j} - 4\sigma^2 \right) \right]} \right). \tag{29}$$

It is important to note that even though the derived expressions in (24) and (29) are for correlated log-normal channels under atmospheric loss effect, they can be applied to uncorrelated log-normal channels under atmospheric loss effect by setting $\rho = 0$ in c_{ij}'.

IV. Numerical Results and Discussions

In this section, a target BER for IM/DD FSO system using OOK of 10^{-9} is assumed [5], λ = 1550 nm and $L = 1$ km. The transmitters branches are assumed to be identically distributed, low and high correlation values are considered (ρ = 0.25 and 0.5). Analytical results with $N = 10$ are compared to Monte Carlo simulation results. Results demonstrate close match for a wide range of SNR values.

Fig. 2 illustrates a correlated log-normal channel with σ = 0.1 and $N_t = 2$. It is revealed that RCs are more power efficient than OSTBCs by about 3 dB for the two considered cases, ρ = 0.25 and 0.5.

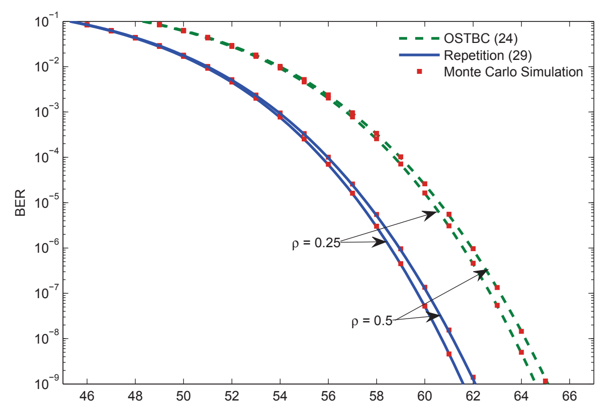

Fig. 2. Correlated log-normal with σ = 0.1, $\mu = -\sigma^2$, and $N_t = 2$ and light fog (α = 20 dB/km).

Figs. 3-6 show the performance of RCs and OSTBCs for different parameters σ, α, ρ and N_t. In Fig. 3, the number of transmitters increases to three, $N_t = 3$. It is shown that RCs with $N_t = 3$ requires 0.6 dB and 0.5 dB less SNR for ρ = 0.25 and 0.5 as compared to RCs with $N_t = 2$, respectively. However, increasing the number of transmitters degrades the performance of OSTBCs by 1 dB and 1.3 dB for

0.25 and 0.5, respectively. Performance degradation can be noticed when comparing the results in Fig. 2 with the results in Fig. 3.

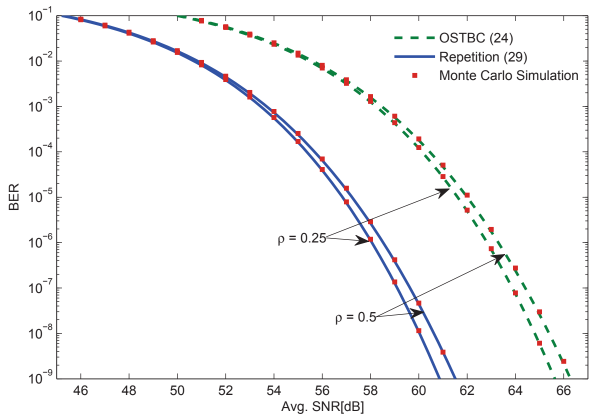

Fig. 3. Correlated log-normal with $\sigma = 0.1$, $\mu = -\sigma^2$, and $N_t = 3$ and light fog (α = 20 dB/km).

In Figs. 4 and 5, a clear air environment with $\sigma = 0.3$ and $\alpha = 0.43$ dB/km is considered. These parameters are chosen considering the inversely proportional relationship between the turbulence strength and attenuation. It is very unlikely that strong turbulence occur during a fog event [23]. From Fig. 4, it can be seen that light fog effect in Fig. 2 is higher than increasing the atmospheric turbulence on the BER performance of the FSO system. The required SNR to achieve the target BER decreases by 25.74 dB and 24.88 dB for RCs and by 25.94 dB and 24.34 dB for OSTBCs with ρ = 0.25 and 0.5, respectively. Simulation results show that RCs still outperform OSTBCs by about 3 dB.

Fig. 5 shows results for $N_t = 3$ and $\sigma = 0.3$. An interesting

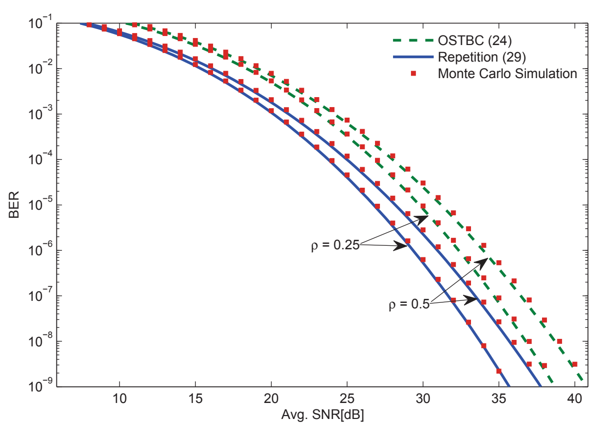

Fig. 4. Correlated log-normal with $\sigma = 0.3$, $\mu = -\sigma^2$, and $N_t = 2$ and clear weather (α = 0.43 dB/km).

observation is the behavior of OSTBCs results, where increasing the number of transmitters enhances the performance unlike the reported behavior in Fig. 3. As compared to the results in Fig. 4, OSTBCs show a SNR gain of 1.4 dB and 0.8 dB with ρ = 0.25 and 0.5, respectively. However, the required SNR to achieve the target BER decreases by 28.24 dB and 26.14 dB for RCs and 28.34 dB and 26.44 dB for OSTBCs with ρ = 0.25 and 0.5, respectively in the absence of light fog.

In Fig. 6 the severe effect of different weather conditions on

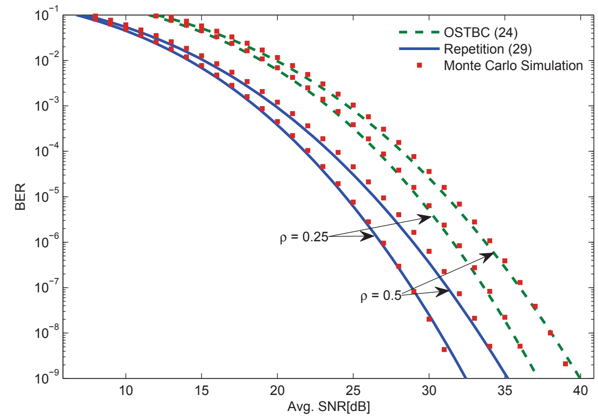

Fig. 5. Correlated log-normal with $\sigma = 0.3$, $\mu = -\sigma^2$, and $N_t = 3$ and clear weather (α = 0.43 dB/km).

the FSO links using three transmitters are investigated using repetition codes with α = 0.1 and ρ = 0.25.

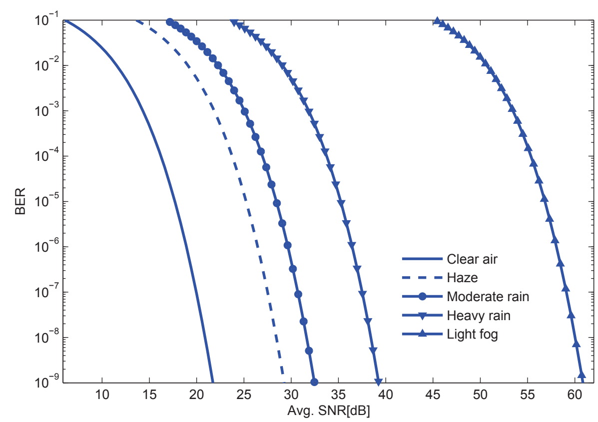

Fig. 6. Correlated log-normal using repetition codes with $\sigma = 0.1$, $\mu = -\sigma^2$, ρ = 0.25 and $N_t = 3$ for different weather conditions.

V. Conclusions

In this manuscript, an approximated BER expressions for non-coherent spatial diversity FSO systems with OOK modulation are derived. The effects of both correlated log-normal channels and path loss due to different conditions are considered. The pdf of correlated log-normal channels is expressed using the MGF approach. Also, an approximated BER expressions for both OSTBCs and RCs in correlated log-normal channels are obtained. It is shown that increasing the number of transmitter enhances the BER performance of RCs but does not always achieve higher SNR gain in OSTBCs. Additionally, RCs is shown to always outperform OSTBCs by at least 3 dB. Finally, the severe effects of different weather conditions on the FSO links are studied where it is shown that fog degrades the FSO performance significantly. Future work will shed more light on the effects of these weather conditions on the performance of FSO and suggest methods to compensate for the performance losses.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support for this work from SNCS Research Center at University of Tabuk under the grant from the Ministry of Higher Education in Saudi Arabia.

REFERENCES

[1] E. Bayaki, D. S. Michalopoulos, and R. Schober, "EDFA-based all-optical relaying in free-space optical systems," *IEEE Transactions on Communications*, vol. 60, no. 12, pp. 3797–3807, Dec. 2012.

[2] C. K. Datsikas, K. P. Peppas, N. C. Sagias, and G. S. Tombras, "Serial free-space optical relaying communications over gamma-gamma atmospheric turbulence channels," *J. Opt. Commun. Netw.*, vol. 2, no. 8, pp. 576–586, Aug. 2010.

[3] B. He and R. Schober, "Bit-interleaved coded modulation for hybrid RF/FSO systems," *IEEE Transactions on Communications*, vol. 57, no. 12, pp. 3753–3763, Dec. 2009.

[4] R. Mesleh, R. Mehmood, H. Elgala, and H. Haas, "Indoor MIMO optical wireless communication using spatial modulation," in *IEEE International Conference on Communications (ICC'10)*, Cape Town, South Africa, May 22–27, 2010, pp. 1–5.

[5] T. A. Tsiftsis, H. G. Sandalidis, G. K. Karagiannidis, and M. Uysal, "Optical wireless links with spatial diversity over strong atmospheric turbulence channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 951–957, Feb. 2009.

[6] A. Mansour, J. Youssef, and K. C. Yao, "Underdetermined BSS of MISO OSTBC signals," in *Independent Component Analysis and Blind Source Separation (ICA 2006)*, Paraty, Brazil, Mar. 15–18 2009, pp. 678–685.

[7] M. Safari and S. Hranilovic, "Diversity gain for near-field MISO atmospheric optical communications," in *IEEE International Conference on Communications (ICC)*, Ottawa, Canada, Jun. 10–15, 2012, pp. 3128–3132.

[8] M. R. Abaza, R. Mesleh, A. Mansour, and A. Alfalou, "MIMO techniques for high data rate free space optical communication system in log-normal channel," in *Proceeding of the International Conference on Technological Advances in Electrical, Electronics and Computer Engineering (TAEECE)*, Konya, Turkey, May 9–11, 2013, pp. 1–5.

[9] M. Safari and M. Uysal, "Do we really need OSTBC for free-space optical communication with direct detection?" *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4445–4448, Nov. 2008.

[10] S. M. Aghajanzadeh and M. Uysal, "Multi-hop coherent free-space optical communications over atmospheric turbulence channels," *IEEE Transactions on Communications*, vol. 59, no. 6, pp. 1657–1663, Jun. 2011.

[11] M. K. Simon and V. Vilnrotter, "Alamouti-type space-time coding for free-space optical communication with direct detection," *IEEE Trans. Wireless Commun.*, vol. 4, no. 1, pp. 35–39, Jan. 2005.

[12] M. Premaratne and F.-C. Zheng, "Orthogonal spacetime block codes for free-space IM/DD optical links," *Electronics Letters*, vol. 43, no. 15, pp. 822–823, Jul. 2007.

[13] E. Bayaki and R. Schober, "Performance and design of coherent and differential space-time coded FSO systems," *Journal of Lightwave Technology*, vol. 30, no. 11, pp. 1569–1577, Jun. 2012.

[14] X. Zhu and J. M. Kahn, "Maximum-likelihood spatial-diversity reception on correlated turbulent free-space optical channels," in *IEEE Conf. on Global Commun.*, vol. 2, San Francisco, CA, Nov.-Dec. 27-1, 2000, pp. 1237– 1241.

[15] N. B. Mehta, A. F. Molisch, J. Wu, and J. Zhang, "Approximating the sum of correlated lognormal or lognormal-Rice random variables," *IEEE Trans. Wireless Commun.*, vol. 6, no. 7, pp. 2690–2699, Jul. 2007.

[16] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, Jul. 1999.

[17] S. M. Navidpour, M. Uysal, and M. Kavehrad, "BER performance of free-space optical transmission with spatial diversity," *IEEE Trans. Wireless Commun.*, vol. 6, no. 8, pp. 2813–2819, Aug. 2007.

[18] H. Moradi, H. H. Refai, and P. G. LoPresti, "A switched diversity approach for multi-receiving optical wireless systems," *Applied Optics*, vol. 50, no. 29, pp. 5606–5614, Oct. 2011.

[19] G. K. Karagiannidis, D. A. Zogas, and S. A. Kotsopoulos, "An efficient approach to multivariate Nakagami-m distribution using greens matrix approximation," *IEEE Trans. Wireless Commun.*, vol. 2, no. 5, pp. 883–889, Sep. 2003.

[20] K. Kiasaleh, "Performance of APD-based, PPM free-space optical communication systems in atmospheric turbulence," *IEEE Transactions on Communications*, vol. 53, no. 9, pp. 1455–1461, Sep. 2005.

[21] H. Moradi, H. H. Refai, and P. G. LoPresti, "Circular MIMO FSO nodes with transmit selection and receive generalized selection diversity," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 3, pp. 1174–1181, Mar. 2012.

[22] M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions with Fomulas, Graphs, and Mathematical Tables*, 9th ed. New York, USA: Dover Publications, 1972.

[23] D. Bushuev and S. Arnon, "Analysis of the performance of a wireless optical multi-input to multi-output communication system," *J. Opt. Soc. Am. A*, vol. 23, no. 7, pp. 1722–1730, Jul. 2006.