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Abstract. Performance analysis of free-space optical (FSO) communication systems in different channel conditions has gained significant attention in literature. Nevertheless, most existing studies consider uncorrelated channel conditions. An uncorrelated channel requires sufficient spacing between transmitters and limits the receiver field of view and link distance. However, this might not be feasible in all applications. Thereby, this paper studies repetition code (RC) and orthogonal space time block code (OSTBC) performance in correlated log-normal FSO channels using intensity modulation and direct detection. An approximate analytical expressions using moment generating function for the average bit error probability are derived. Our simulation results show that RCs are superior to OSTBCs in correlated channel conditions. © *2014 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.53.1.XXXXXX]

1 Introduction

Free-space optical (FSO) technology has several advantages compared with radio frequency (RF), such as high data rates, license-free operation, high security, and ease of deployment. However, the performance of FSO systems can be highly affected by fog and atmospheric turbulence.[1–3] Atmospheric turbulence can be considered as one of the main problems facing FSO communication systems. The nonhomogeneous changes in pressure and temperature lead to several changes in the refractive index, which result in rapid fluctuations in the received signal and limit the performance of the FSO communication system.[1,2,4,5]

Spatial diversity has the ability to mitigate the degradation of the bit error rate (BER) caused by atmospheric turbulence and maximizes the data rate of the system. Furthermore, it can improve the link reliability, decreases the blockage probability, and limits the need for active tracking due to laser misalignment.[1,4,6–10] Two codes are generally considered in FSO spatial diversity systems. Namely, repetition codes (RCs) and orthogonal space time block codes (OSTBCs).

In the RC system, the same signal is transmitted simultaneously from the available transmitters. The advantages of such a transmission technique are very limited in RF and FSO wireless systems using a heterodyne (coherent) reception. However, heterodyne reception is not preferred in FSO systems due to its high cost and complexity. An alternative and preferred transmission/reception method is intensity modulation with direct detection (IM/DD).[11] A study in Ref. 2 considers the IM/DD RCs system with on–off keying (OOK) modulation over FSO log-normal channels. Reported results[2] demonstrate that significant performance gains can be achieved.

A modified version of Alamouti's code, which allows the use of unipolar pulsed modulation techniques for IM/DD

links is reported in Ref. 12. The main idea is to represent the negative signal of a unipolar signal by the 1's complement (i.e., bitwise NOT) of the positive signal. In Ref. 11, the authors have extended the previous algorithm to handle up to eight transmit apertures and they showed that RCs outperform OSTBCs using IM/DD in uncorrelated log-normal channels. In Ref. 13, the authors show that coherent and differential OSTBCs in FSO systems outperform their counterpart RC systems at the expense of laborious receiver.

Previous studies have considered the case of uncorrelated channels assuming the spacing between transmitters is larger than the fading correlation length, but not exceeding the capture zone of the receiver, which should be less than θL m, where θ is the field of view of the receiver in radians (rad) and L is the link distance in meter (m).[12] For example, if $L = 1$ km and $\theta \cong 10$ mrad, then the transmitters should be <10 m apart. However, the last assumption may be difficult in practice as available space for the transmitters may not be sufficient for this requirement.[4]

A simple and general method to approximate the probability density functions (PDF) of uncorrelated and correlated log-normal channels using moment generating function (MGF) is reported in Ref. 14. Another method for log-normal channels distribution approximation can be done using the Erlang distribution.[15] The use of Erlang distribution leads to an approximate closed-form expression of the BER with log-normal channel variance not exceeding 3 dB. Such variance is suitable for FSO communication systems.[15] However, it is generally very difficult to find an optimal Erlang PDF for the employed log-normal channels.

Hence, the MGF approach is considered in this study to analyze FSO system performance employing RCs and OSTBCs using IM/DD in the presence of correlated log-normal channel conditions. Reported results demonstrate a

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close match between numerical Monte Carlo simulations and analytical results for a wide range of signal to noise ratio (SNR), which corroborates the exactness of our derivation.

The remainder of this paper is organized as follows: the FSO diversity model is presented in Sec. 2. In Sec. 3, performance analysis is presented. Numerical results and discussions are given in Sec. 4. Finally, conclusions are summarized in Sec. 5.

2 System Model

A synoptic diagram of the considered system model is depicted in Fig. 1. The system considers N_t transmitters and a single receiver. Source bits are modulated using OOK and encoded by a multiple-input single-output (MISO) encoder. The encoder considers two techniques for transmission, namely OSTBCs and RCs. In RC systems, the same signal is transmitted simultaneously from the available transmitters, whereas in OSTBCs, full-rate real orthogonal matrices, $\mathbf{G}$, for $N_t \leq 8$, are considered.[16] In Ref. 11, 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 the synchronized laser diodes. The transmitted light propagates over correlated log-normal channel and suffers from 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 the received signal light intensity after turbulence, I_i is given by[2]

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

where $s(t)$ is the transmitted information symbol, η is the optical to electrical conversion coefficient, $h_i = \exp(2X_i)$ 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. Hence, h_i is a log-normal random variable (RV) with PDF given by[17]

$$f(h_i) = \frac{1}{h_i\sqrt{8\pi\sigma^2}} \times \exp\left(-\frac{(\ln(h_i)-2\mu)^2}{8\sigma^2}\right). \tag{3}$$

To ensure that the fading channel does not attenuate or amplify the average power, the fading coefficients are normalized as $\mathbf{E}[h_i] = e^{2(\mu+\sigma^2)} = 1$. I_o in Eq. (2) is the received average signal light intensity without considering the channel effect and $n(t)$ is the AWGN at the receiver input. The noise is mainly due to shot noise which dominates
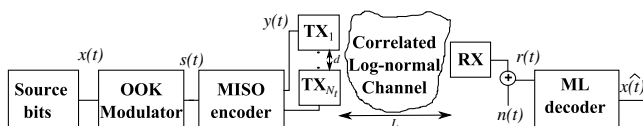
over other noise sources such as thermal, signal-dependent or dark noises.[11]

The spatial covariance matrix $\mathbf{\Gamma}$ coefficients, modeling the spatial correlation among transmitters, are given by[2]

$$\Gamma_{ij} = \sigma^2 \times \rho^{|i-j|}, \tag{4}$$

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 Ref. 4, ρ is a function of the separation distance d between transmitters,

$$\rho = \exp\left(-\frac{d}{d_o}\right), \tag{5}$$

where the correlation length $d_o \approx \sqrt{\lambda L}$ with λ being the wavelength and L is the linear propagation distance between the transmitters and the receiver. This correlation model is called the exponential model[18] and corresponds to the scenario of a multichannel transmission from linearly equispaced transmitters. From Eq. (5), the correlation of combined signals decays by increasing the spacing between the transmitters.

At the receiver side, maximum-likelihood decoder is considered to decode the received signals.[16]

3 Performance Analysis

3.1 Orthogonal Space Time Block Codes

The PDF of the instantaneous SNR γ_i, $1 \leq i \leq N_t$, of correlated jointly log-normal channel is given by[17]

$$f(\gamma_1, \cdots, \gamma_{N_t}) = \frac{\exp\left(-\frac{1}{32}Z(\mathbf{\Gamma})^{-1}Z^T\right)}{4^{N_t}\sqrt{(2\pi)^{N_t}(\det[\mathbf{\Gamma}])}\Pi_{i=1}^{N_t}\gamma_i}, \tag{6}$$

where $Z = [\ln(\frac{\gamma_1}{\overline{\gamma}_1}), \cdots, \ln(\frac{\gamma_{N_t}}{\overline{\gamma}_{N_t}})] - 4\mu$, $\overline{\gamma}_i$ 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 Eq. (6) is given by[19]

$$\gamma_i = \frac{(\eta I_i)^2}{N_o}. \tag{7}$$

The conditional BER for FSO system using OSTBCs is given by[11]

$$P(e|h) = Q\left[\sqrt{\frac{E_b}{2N_o}\sum_{i=1}^{N_t} h_i^2}\right], \tag{8}$$

with E_b being the average electrical energy of the transmitted pulse at each transmitter given by[11]

$$E_b = \left(\frac{\eta I_o}{N_t}\right)^2. \tag{9}$$

The factor N_t is included in Eq. (9) 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.

Fig. 1 Synoptic diagram of the proposed model.

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

$$Q(y) \triangleq \frac{1}{\sqrt{2\pi}} \int_y^\infty \exp\left(-\frac{x^2}{2}\right) dx$$
$$= \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \exp\left(-\frac{y^2}{2\sin^2\theta}\right) d\theta. \quad (10)$$

Substituting Eq. (9) into Eq. (8) and using Eq. (2) yields

$$P(e|h) = Q\left(\sqrt{\frac{\eta^2}{2N_o(N_t)^2} \sum_{i=1}^{N_t} I_i^2}\right). \quad (11)$$

Using Eq. (7), the conditional BER with respect to the SNR becomes

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

Using the PDF of the instantaneous SNR γ_i in Eq. (6), the average bit error probability of OSTBCs is given by

$$\text{BER} = \int_0^\infty \cdots \int_0^\infty Q\left(\sqrt{\frac{\sum_{i=1}^{N_t} \gamma_i}{2(N_t)^2}}\right) f(\gamma_1, \cdots, \gamma_{N_t}) d\gamma_1 \cdots d\gamma_{N_t}. \quad (13)$$

According to Ref. 21, the MGF is defined by

$$\Psi(s) = \int_0^\infty \cdots \int_0^\infty f(\gamma_1, \cdots, \gamma_{N_t}) \exp\left[-s \sum_{i=1}^{N_t} \gamma_i\right] d\gamma_1 \cdots d\gamma_{N_t}. \quad (14)$$

With the use of Eq. (6) and after few algebraic manipulations, the PDF of instantaneous branch SNR for the given branch i, γ_i, is

$$f(\gamma_i) = \frac{1}{\sqrt{32\pi\sigma^2}\gamma_i} \exp\left[-\frac{\left(\ln\left(\frac{\gamma_i}{\bar{\gamma}_i}\right) + 4\sigma^2\right)^2}{32\sigma^2}\right]. \quad (15)$$

The MGF of the RV γ_i is then given by

$$\Psi(s) = \int_0^\infty \exp(-s\gamma_i) \frac{1}{\sqrt{32\pi\sigma^2}\gamma_i}$$
$$\times \exp\left[-\frac{\left(\ln\left(\frac{\gamma_i}{\bar{\gamma}_i}\right) + 4\sigma^2\right)^2}{32\sigma^2}\right] d\gamma_i. \quad (16)$$

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

$$\Psi(s) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^\infty \exp(-x^2) \exp\left[-s\bar{\gamma}_i \exp\left(\sqrt{32\sigma^2}x - 4\sigma^2\right)\right] dx. \quad (17)$$

Using Hermite polynomial approximation gives[22]

$$\int_{-\infty}^\infty \exp(-x^2) g(x) dx \approx \sum_{i=1}^N w_i g(x_i), \quad (18)$$

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

Applying Eq. (18) on Eq. (17) yields

$$\Psi(s) \approx \frac{1}{\sqrt{\pi}} \sum_{i=1}^N w_i \exp\left[-s\bar{\gamma}_i \exp\left(\sqrt{32\sigma^2}x_i - 4\sigma^2\right)\right]. \quad (19)$$

Using Eqs. (19), (6), and following a similar approach as in Ref. 14, the general form of the MGF in a correlated log-normal channel is given by

$$\Psi(s) \approx \sum_{n_1=1}^N \cdots \sum_{n_{N_t}=1}^N \left[\prod_{i=1}^{N_t} \frac{w_{n_i}}{\sqrt{\pi}}\right]$$
$$\times \exp\left(-s \sum_{i=1}^{N_t} \bar{\gamma}_i \left[\exp\left(\sqrt{32} \sum_{j=1}^{N_t} c'_{ij} x_{n_j} - 4\sigma^2\right)\right]\right), \quad (20)$$

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 Ref. 22 (Table 25.10), and c'_{kj} is the (k, j)'th coefficient of $\mathbf{\Gamma}_{\text{sq}} = \mathbf{\Gamma}^{1/2}$.

Using Eq. (20) 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, after some manipulations, is derived as

$$\text{BER} \approx \sum_{n_1=1}^N \cdots \sum_{n_{N_t}=1}^N \left[\prod_{i=1}^{N_t} \frac{w_{n_i}}{\sqrt{\pi}}\right]$$
$$\times Q\left(\sqrt{\frac{\bar{\gamma}}{2N_t^2} \sum_{i=1}^{N_t} \left[\exp\left(\sqrt{32} \sum_{j=1}^{N_t} c'_{ij} x_{n_j} - 4\sigma^2\right)\right]}\right). \quad (21)$$

3.2 Repetition Codes

The conditional BER of FSO system using RCs is given by[11]

$$P(e|h) = Q\left(\sqrt{\frac{E_b}{2N_o}} \sum_{i=1}^{N_t} h_i\right). \quad (22)$$

Using the alternative definition of the Q-function in Eq. (10), the BER of RC systems over correlated log-normal channel is given by

$$\text{BER} = \frac{1}{\pi} \int_0^\infty \cdots \int_0^\infty \int_0^{\frac{\pi}{2}} \exp\left(-\frac{\left(\sum_{i=1}^{N_t} \sqrt{\gamma_i}\right)^2}{4N_t^2 \sin^2\theta}\right)$$
$$\times f(\gamma_1, \cdots, \gamma_{N_t}) d\theta d\gamma_1 \cdots d\gamma_{N_t}. \quad (23)$$

Let us note that the MGF approach cannot be used to represent Eq. (23), 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

$$I_1 = \left(\sum_{i=1}^{N_t} \sqrt{\gamma_i} \right)^2 \approx I_2 = N_t \sum_{i=1}^{N_t} \gamma_i. \tag{24}$$

Monte Carlo simulation results with 10^5 samples are conducted to verify the validity of the proposed approximation in Eq. (24). The relative estimation error percent, $\xi = 100 \times \left(\frac{I_1 - I_2}{I_1} \right) \leq 8.2\%$, is calculated for different σ values. Let us note that the maximum value of σ for log-normal channel corresponds to the maximum scintillation index (SI) value for log-normal channel, which is ≤ 0.75.[20] The relation between SI and σ is defined in Ref. 17 as $\sigma = \left(\frac{\sqrt{\ln(SI)+1}}{2} \right)$. Hence, σ should be ≤ 0.374. Estimation error percents for different values of σ are tabulated in Table 1, where it is shown that the maximum error is $\leq 8.2\%$.

Hence, substitute Eq. (24) in Eq. (23) and using Eq. (14) yields

$$\text{BER} \approx \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \Psi \left(\frac{1}{4N_t \sin^2 \theta} \right) d\theta. \tag{25}$$

From Eqs. (20) and (25) and assuming that all SNR averages from the transmitters are equal, an approximate novel expression for the BER of RC systems over correlated lognormal channels, after some manipulations, is derived as

$$\text{BER} \approx \sum_{n_1=1}^{N} \cdots \sum_{n_{N_t}=1}^{N} \left[\prod_{i=1}^{N_t} \frac{w_{n_i}}{\sqrt{\pi}} \right]$$
$$\times Q \left(\sqrt{ \frac{\bar{\gamma}}{2N_t} \sum_{i=1}^{N_t} \left[\exp \left(\sqrt{32} \sum_{j=1}^{N_t} c'_{ij} x_{n_j} - 4\sigma^2 \right) \right] } \right). \tag{26}$$

It is important to note that even though the derived expressions in Eqs. (21) and (26) are for correlated log-normal channels, they can be applied to uncorrelated log-normal channels by setting $\rho = 0$ in c'_{ij}.

4 Numerical Results and Discussions

In Fig. 2, the relation between the correlation effect and the separation distance between the transmit units is studied. The selected wavelength is $\lambda = 1550$ nm and different propagating distances and correlation lengths are considered. Simulation results show that if a correlation coefficient of $\rho \leq 10^{-3}$ is to be maintained, then the distance between

Table 1 Error due to approximation.

σ	ρ	$\xi(\%)$
0.1	0.5	0.4
0.1	0.25	0.7
0.374	0.5	5.9
0.374	0.25	8.2

the transmit units should be at least seven times the correlation length.

In Figs. 3–6, a target BER for the FSO system of 10^{-9} is assumed.[19] The diversity branches are assumed to be identically distributed, and low or high correlation values are considered ($\rho = 0.25$ and 0.5).

In Fig. 3, correlated log-normal channel with $\sigma = 0.1$ and $N_t = 2$ is employed. Analytical results with $N = 10$ are compared to Monte Carlo simulation results. Results demonstrate the close match for a wide range of SNR values. It is revealed that RCs are more power efficient than OSTBCs by about 3 dB for the two considered cases, $\rho = 0.25$ and 0.5.

Figures 4–6 study the performance of RCs and OSTBCs for different parameters σ, ρ, and N_t. In Fig. 4, the number of transmitters increases to three, $N_t = 3$. It is shown that RCs with $N_t = 3$ requires 0.6 and 0.5 dB less SNR for $\rho = 0.25$ 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 and 1.3 dB for 0.25 and 0.5, respectively. Performance degradation can be noticed when comparing the results in Fig. 3 with the results in Fig. 4.

In Figs. 5 and 6, a different log-normal parameter $\sigma = 0.374$ with $N_t = 2$ is employed. Figure 5 shows that increasing the atmospheric turbulence degrades the BER performance of the FSO system severely. The required SNR to achieve the target BER increases by 18.9 and 21 dB for RCs and by 19.3 and 21.5 dB for OSTBCs codes with $\rho = 0.25$ and 0.5, respectively, compared to $\sigma = 0.1$ with $N_t = 2$. Simulation results show that RCs still outperform OSTBCs by about 3 dB.

Figure 6 shows results for $N_t = 3$ and $\sigma = 0.374$. An interesting observation is the behavior of OSTBCs results, where increasing the number of transmitters enhances the performance, unlike the reported behavior in Fig. 4. As compared to the results in Fig. 5, OSTBCs show an SNR gain of 1.95 and 2 dB for $\rho = 0.25$ and 0.5, respectively.

The behavior of OSTBC at low turbulence in FSO can be attributed to the fact that the channel paths from different transmitters to the receiver are highly correlated at low turbulence. In fact, if there is no turbulence, then the channel will be Gaussian and no diversity gain will be achieved. For Gaussian channels, the best system configuration is an SISO system, since in OSTBCs, the overall transmit power will be divided among the transmit antennas. Thereby, OSTBC systems with a low number of transmitters at low turbulence
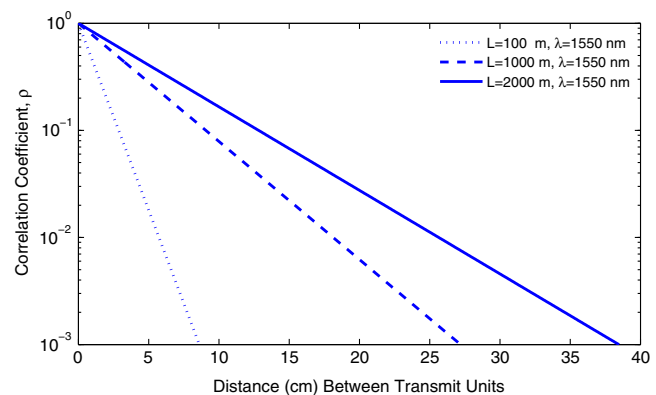

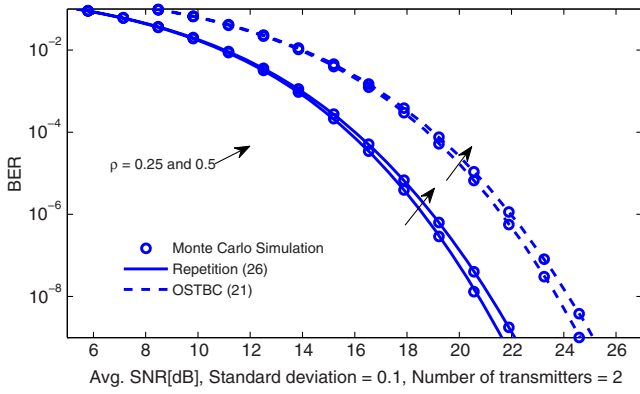**Fig. 2** Correlation effect versus distance between transmit units for difference propagation distances.

Fig. 3 Correlated log-normal with $\sigma = 0.1$, $\mu = -\sigma^2$ and $N_t = 2$.
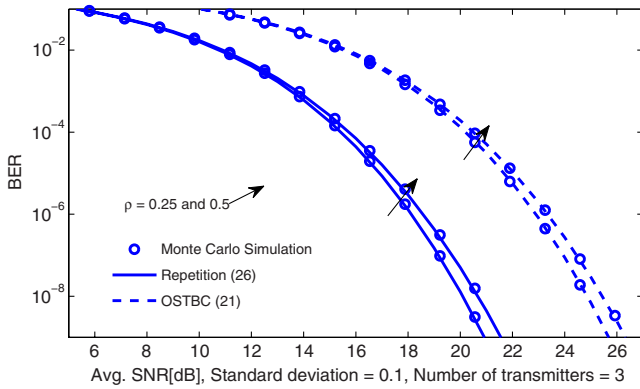

Fig. 4 Correlated log-normal with $\sigma = 0.1$, $\mu = -\sigma^2$ and $N_t = 3$.
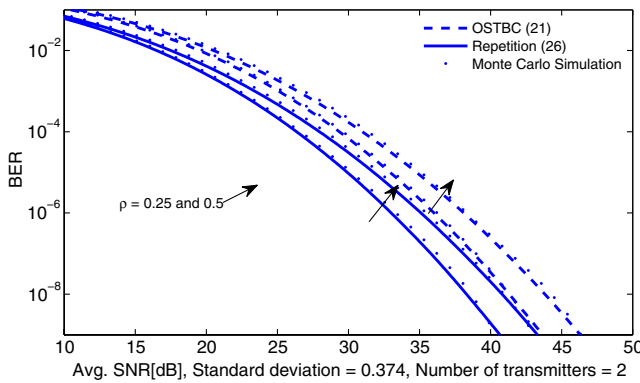

Fig. 5 Correlated log-normal with $\sigma = 0.374$, $\mu = -\sigma^2$ and $N_t = 2$.
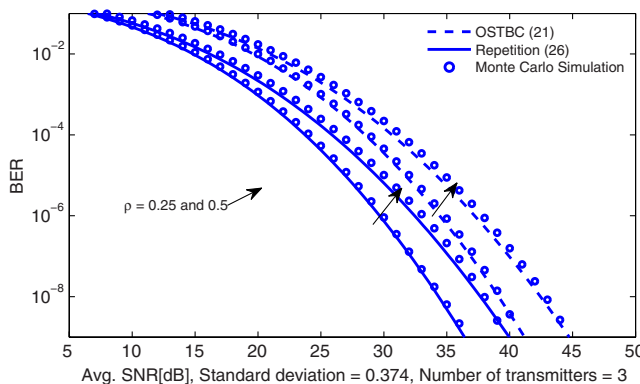

Fig. 6 Correlated log-normal with $\sigma = 0.374$, $\mu = -\sigma^2$ and $N_t = 3$.

channel conditions outperform their counterpart systems with a higher number of transmitters.

The required SNR, under more severe turbulence, to achieve the target BER increases by 14.5 and 17.7 dB for RCs and 15.4 and 17.6 dB for OSTBCs with $\rho = 0.25$ and 0.5, respectively, compared to $\sigma = 0.1$ with $N_t = 3$.

5 Conclusions

The novel performance analysis of RCs and OSTBCs in an FSO system is investigated in this paper over correlated log-normal channels. Both schemes are shown to be useful in mitigating the turbulence fading effect and improving the BER performance. However, results revealed that RC systems always outperform their counterpart OSTBC systems. Furthermore, it is shown that the SNR gain of RC systems always increases with increasing the number of transmitters. On the contrary, increasing the number of transmitters of OSTBCs system does not always achieve higher SNR gain and the achieved gain depends on the channel conditions. Analytical and simulation results are shown to match over wide range of SNR and for different system parameters.

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