New Performance Results for QAM OFDM RoFSO Over K and Exponentially Modeled Turbulence Channels

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Abstract. Free space laser communications are gaining popularity due to their high bandwidth and security transmission that they offer, the license free spectrum use and the sufficient reliability for operational and installation costs compared to RF communication systems. The radio on free space optics (RoFSO) is a technology of modulating RF signals on optical carriers for transmission over the free space. However, the performance of those systems depends strongly on the atmospheric conditions. In this work, we study a RoFSO communication link which is using the orthogonal frequency division multiplexing (OFDM) scheme with quadrature amplitude modulation (QAM) format over the atmospheric turbulence channel, modeled either with K or negative exponential distribution. Using a very recently presented accurate approximation for the Q-function we derive new closed form mathematical expressions for the estimation of the BER and the outage probability of a QAM OFDM RoFSO link over turbulence channels modeled either with the K or the NE distribution. Finally, we investigate the performance of these optical wireless communication systems with numerical results using the derived expressions and realistic link's parameters.

Keywords: BER, Outage Probability, Free Space Optical Communications, OFDM, PSK.

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I. INTRODUCTION

Free Space Optical (FSO) communication systems has attracted significant research and commercial interest due to their high data rates, high security level without need of licensing fees and tariffs, lower power consumption, ease of portability, quick deployment and lower overall installation and operational costs compared to conventional radio links and fiber optics [1]-[7].

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Radio on free space optics (RoFSO) is a technology similar to the radio over fiber (RoF) where the radio frequency signals are transmitted by optical devices wirelessly, excluding the fiber medium [8]-[11]. Despite the great benefits that they render, their efficiency is influenced by the atmospheric conditions and many harmful effects that affect the atmospheric channel can lead to severe signal fading or even outage of the signal. The most important effects are related to the absorption, scattering and refractive index fluctuations. The absorption and scattering processes referred as extinction caused by the air composition from molecules such as water, carbon dioxide, ozone and other aerosol particulate matter usually larger than molecules like particles formed from gaseous emissions, dust, sea-salt particles etc, [1]-[7], [12]-[19].

The refractive index fluctuations in atmosphere represent a serious mitigation factor which is generated by the turbulence effect. This effect is created when changes in temperature cause inhomogeneities in the refractive index of the air in the form of small eddies. The random temporal and spatial variations in the refractive index affect the intensity level at the receiver which fluctuates, as well. These intensity fluctuations, also known as scintillation effect, have been studied extensively and many statistical models have been proposed to model accurately these signal variations. In this work, we assume the K and the negative exponential (NE) distributions which are suitable for strong and saturate turbulence conditions respectively, [3], [9], [17]-[26].

The orthogonal frequency division multiplexing (OFDM) scheme is a special type of multiple subcarrier modulation (MSM) which has been adopted in many digital audio broadcasting services, digital subscriber lines (DSL), wireless local area networks (WLAN), modern cellular mobile networks etc. The subcarrier modulation can be done with the appropriate, for each specific case, scheme, e.g. quadrature amplitude modulation (QAM), phase shift keying modulation (PSK). The OFDM technique offers high spectral efficiency, robustness against frequency selective fading and avoids intersymbol and narrow-band interference. On the other hand, the large number of subcarriers creates undesired high peak to average power ratios (PAPR). The high PAPR combined with associated addition of dc bias to the OFDM signal in order to be applicable to intensity modulation direct detection IM/DD optical systems, cause efficiency reduction due to intermodulation distortions by the nonlinear laser diode LD characteristics of the transmitter, [9], [11], [27]-[32].

As a consequence of the above mentioned phenomena, we study a RoFSO link using a QAM OFDM scheme and taking into account the atmospheric turbulence effect, modeled either with K or NE distribution, we derive new accurate closed form mathematical expressions for the evaluation of its performance by means of the estimation of its average BER and outage probability.

II. THE CHANNEL MODEL

The optical communication system under consideration is a terrestrial QAM OFDM RoFSO communication link under the action of atmospheric turbulence modeled with the K or the NE distribution models. The initial high data rate streams are split into lower rate parallel streams and then transmitted simultaneously by multiple narrow band orthogonal subcarriers. The OFDM signal for N subcarriers, just before the LD after up conversion to the carrier frequency f_c, is given as, [9]:

$$s_{OFDM}(t)=\sum_{n=0}^{N-1}s_n(t)=\sum_{n=0}^{N-1}X_n\exp[i(\omega_n+2\pi f_c)t] \quad for\ 0\le t<T_s \tag{1}$$

where each orthogonal subcarrier has an angular frequency of $\omega_n=2\pi n/T_s$, n=0,…, N-1, T_s is the OFDM symbol duration and X_n represents the complex data symbol of the n_{th} subcarrier which is mapped according to the selected modulation format which in our case is the QAM scheme. The transmitted optical power $P(t)$ is formulated as follows, [9]:

$$P(t)=P_t\left[1+\sum_{n=0}^{N-1}m_n s_n(t)+a_3\left(\sum_{n=0}^{N-1}m_n s_n(t)\right)^3\right] \tag{2}$$

where, P_t, is the average transmitted optical power, a_3 stands for the third order nonlinearity coefficient of the LD and m_n is the optical modulation index (OMI) per subcarrier defined as $m_n=\Delta I/(I_b-I_{th})$, with ΔI being the variation of the laser driving current around a bias point and I_b, I_{th}, stand for the bias and threshold laser currents respectively. The received optical power after the atmospheric propagation is $P_r(t)=P(t)L_{tot}I+n(t)$, where L_{tot} is the overall attenuation factor which encompasses the beam extinction from scattering and absorption, misalignment losses and losses due to scintillation. The additive white Gaussian noise (AWGN) of the channel is characterized as $n(t)$ and I is the instantaneous normalized irradiance arriving at the receiver which fluctuates rapidly due to scintillation effect caused by the turbulence. The photo generated current by the impinging power on the avalanche photodiode PD of the receiver is [9]:

$$i(t,I)=I_0\left[1+\sum_{n=0}^{N-1}m_n s_n(t)+a_3\left(\sum_{n=0}^{N-1}m_n s_n(t)\right)^3\right]+n_{opt}(t) \tag{3}$$

with $I_0=\rho L_{tot}P_t I$ which is the dc of the photo-induced current $i(t,I)$, ρ is the responsivity of the PD, while n_{opt} stands for the optical noise which can be considered as AWGN with zero mean and $N_0/2$ variance, with $N_0=4K_BTF/R_L+2qI_0+I_0^2(RIN)$. In the last expression, K_B is the Boltzmann's constant, T is the temperature, F is the noise figure of the receiver, R_L the load resistor at the PD's side, q the electron charge and RIN is the relative intensity noise from the laser which is a function of the square of the optical power.

Moreover, the effect of intermodulation distortion due to the finite linear operating range of the LD transmitter is another factor that degrades the efficiency of the optical system. The IMD noise for the N subcarriers is as [9], [11]:

$$\sigma_{IMD,n}^2=\frac{9a_3^2m_n^6\rho^2L_{tot}^2P_t^2I^2}{128}\left(2n(N-n+1)+N(N-5)+2-\frac{(-1)^n-(-1)^{2N+n}}{2}\right)^2 \tag{4}$$

The total carrier to noise plus distortion ratio (CNDR) for each subcarrier including the optical noise and the intermodulation distortion, by assuming that the total noise, i.e. IMD and optical noise, are Gaussian distributed [9], [11], and by averaging them scintillation [9], [11], is given as:

$$CNDR_n(I)\approx\frac{m_n^2\rho^2L_{tot}^2P_t^2I^2}{2\left([N_0/T_S]_{AV}+[\sigma_{IMD}^2]_{AV}\right)} \tag{5}$$

From (5), the average value $[CNDR_n]_{AV}$, can be obtained by averaging the quantities N_0/T_s , σ_{IMD}^2 over I and n respectively and considering that the average value of I is normalized to unity. In this case is given as [9], [11]:

$$[CNDR_n]_{AV} = \frac{(m_n \rho L_{tot} P_t)^2}{2([N_0/T_s]_{AV} + [\sigma^2_{IMD}]_{AV})} \tag{6}$$

III. THE K AND EXPONENTIALLY MODELED TURBULENCE CHANNEL

The random changes in the refractive index of the atmospheric path are caused by the turbulence effect which can degrade severely the performance of an FSO communication system. Rapid fluctuations on the intensity level at the receiver, the well known scintillations, are related with turbulence induced phenomena like beam spreading out of the transmit path and a continuous random motion of the beam around the receiver's centre. These signal fades create random signal losses or even complete loss of the signal in the case of outage. In order to estimate these signal fluctuations many statistical models have been proposed according to the turbulence strength. In this work we manipulate the K and NE distribution models which are ideal for strong and saturate turbulence conditions respectively. Thus, the probability density function (PDF) for the K distribution model for the normalized irradiance *I*, is given as, [23]-[25]:

$$f_{K,I}(I) = \frac{2a^{\frac{a+1}{2}}}{\Gamma(a)} I^{\frac{a-1}{2}} K_{a-1}\left(2\sqrt{aI}\right) \tag{7}$$

While, the corresponding PDF for the NE distribution model has the following form, [22], [26]:

$$f_{NE,I}(I) = \exp(-I) \tag{8}$$

Moreover, by integrating the expression (7), we conclude to the following cumulative distribution function (CDF) for the K-distribution, [25]:

$$F_{K,I}(I) = \frac{(aI)^{\frac{a+1}{2}}}{\Gamma(a)} G^{2,1}_{1,3}\left(aI \,\middle|\, \begin{matrix} 1-\frac{a+1}{2} \\ \frac{a-1}{2}, \frac{1-a}{2}, -\frac{a+1}{2} \end{matrix} \right) \tag{9}$$

while, by integrating (8), we obtain the following CDF for the NE distribution:

$$F_{NE,I}(I) = 1 - \exp(-I) \tag{10}$$

IV. THE AVERAGE BER

In this section we derive the appropriate expressions for the estimation of a significant performance metric of communication link which is the average BER, [3], [5], [9], [11], [26]. By assuming, Gray code mapping at the transmitter, an accurate expression for the BER estimation of an *M*-QAM OFDM with *N* subcarriers is given as, [33]:

$$P_{b,M-QAM}=\frac{1-M^{-1/2}}{N\log_2(M)}\sum_{n=0}^{N-1}\left[2erfc\left(\sqrt{\frac{3CNDR_{n,l}(I)}{2(M-1)}}\right)-\right.$$
$$\left.-\left(1-M^{-1/2}\right)erfc^2\left(\sqrt{\frac{3CNDR_{n,l}(I)}{2(M-1)}}\right)\right] \quad (11)$$

where *erfc(.)*, stands for the complementary error function and *M* is the modulation format parameter of the QAM scheme. By integrating (11), using the suitable PDF according the atmospheric turbulence conditions, over the normalized irradiance, the average BER is estimated as, [11]:

$$P_{b,M-QAM,Av}=\frac{\left(1-M^{-1/2}\right)}{N\log_2(M)}\sum_{n=0}^{N-1}\int_0^{\infty}\left[2erfc\left(\sqrt{\frac{3CNDR_{n,l}(I)}{2(M-1)}}\right)-\right.$$
$$\left.-\left(1-\sqrt{M^{-1}}\right)erfc^2\left(\sqrt{\frac{3CNDR_{n,l}(I)}{2(M-1)}}\right)\right]f_I(I)dI \quad (12)$$

By substituting (9) or (10) in (12), using the very recently presented accurate approximation for the estimation of the complementary error function, [34], i.e. $erfc(x)\approx\left(5e^{-4x^2}+4e^{-11x^2/10}+e^{-x^2}\right)/12$, and substituting the functions *erfc(.)* and *exp(.)* with the corresponding Meijer ones [35], we solve the integral of (12). Thus, for the case of strong turbulence conditions, i.e. using the PDF of the K-distribution model, we conclude to the following closed form mathematical expression for the estimation of the average BER of the M-QAM OFDM RoFSO link:

$$P_{b,K,M-QAM,AV}=\frac{\left(1-\sqrt{M}^{-1}\right)2^a}{N\pi\Gamma(a)\log_2(M)}\times$$
$$\times\sum_{n=0}^{N-1}\left[\frac{1}{\sqrt{\pi}}\Lambda-\frac{\left(1-\sqrt{M}^{-1}\right)}{288}\left[25\Xi(192)+16\Xi\left(\frac{264}{5}\right)+\right.\right.$$
$$\left.\left.+40\Xi\left(\frac{612}{5}\right)+\Xi(48)+10\Xi(120)+8\Xi\left(\frac{252}{5}\right)\right]\right] \quad (13)$$

where

$\Xi(x)=G_{4,1}^{1,4}\left(x\delta\left|\begin{matrix}\frac{1-a}{2},\frac{2-a}{2},0,\frac{1}{2}\\0\end{matrix}\right.\right)$ and $\Lambda=G_{5,2}^{2,4}\left(24\delta\left|\begin{matrix}\frac{1-a}{2},\frac{2-a}{2},0,0.5,1\\0,0.5\end{matrix}\right.\right)$ with $\delta=\frac{[CNDR_n]_{AV}}{a^2(M-1)}$.

Furthermore, the corresponding expression for the case of the NE distribution is given as:

$$P_{b,NE,M-QAM,AV}=\frac{2\left(1-\sqrt{M}^{-1}\right)}{N\pi\log_2(M)}\times$$
$$\times\sum_{n=0}^{N-1}\left[\Omega-\frac{\sqrt{\pi}\left(1-\sqrt{M}^{-1}\right)}{288}\left[25\Psi(48)+16\Psi\left(\frac{66}{5}\right)+\right.\right. \tag{14}$$
$$\left.\left.+40\Psi\left(\frac{153}{5}\right)+\Psi(12)+10\Psi(30)+8\Psi\left(\frac{63}{5}\right)\right]\right]$$

with

$\Omega=G_{3,2}^{2,2}\left(\frac{6[CNDR_n]_{AV}}{(M-1)}\middle|\begin{matrix}0,\,0.5,\,1\\0,0.5\end{matrix}\right)$ and $\Psi(x)=G_{2,1}^{1,2}\left(\frac{x[CNDR_n]_{AV}}{(M-1)}\middle|\begin{matrix}0,0.5\\0\end{matrix}\right)$.

It should be mentioned here, that the above derived new closed form expression obtained in (14) is a more accurate and different than the one obtained from [11] and [36].

IV. THE OUTAGE PROBABILITY

A significant metric for the reliability estimation of the optical link, is the outage probability. This quantity shows the probability of the CNDR at the receiver falls below a critical value which is the threshold of the receiver. In this case the link cannot work and the information signal cannot be recognized by the receiver, [3], [5], [9], [15], [26]. The atmospheric turbulence leads to fast and large irradiance fluctuations which could decrease significantly the value of the instantaneous normalized irradiance, I, at the receiver and fall below the critical threshold I_{th} defined by the receiver's sensitivity. Thus, the outage probability for an OFDM RoFSO link is given as [9]:

$$P_{out}=\frac{1}{N}\sum_{n=0}^{N-1}P_{out,n}=$$
$$=\frac{1}{N}\sum_{n=0}^{N-1}\Pr\left(I_n<I_{n,th}\right)=\frac{1}{N}\sum_{n=0}^{N-1}F_{I_n}\left(I_{n,th}\right) \tag{15}$$

where $CNDR_n$ and $CNDR_{n,th}$, is the instantaneous and the threshold carrier to noise plus distortion ratio for the n_{th} OFDM subcarrier of the RoFSO link. Using equations (9), (10) with a transformation we express the CDFs as a function of $CNDR_n$. Hence the outage probability is given as:

$$P_{out} = \frac{1}{N}\sum_{n=0}^{N-1} F_{CNDR_n}\left(\sqrt{\frac{CNDR_{n,th}}{[CNDR_n]_{AV}}}\right) \quad (16)$$

Next, from (9) and (16), the final closed form expression for the estimation of the outage probability of the OFDM RoFSO link under strong turbulence conditions, i.e. modeled with the K-distribution model which can be obtained from the gamma gamma [9], is given as:

$$P_{out,K} = \frac{1}{N}\sum_{n=0}^{N-1}\left[\frac{\left(a\sqrt{\frac{CNDR_{n,th}}{[CNDR_n]_{AV}}}\right)^{\frac{a+1}{2}}}{\Gamma(a)} G_{1,3}^{2,1}\left(a\sqrt{\frac{CNDR_{n,th}}{[CNDR_n]_{AV}}}\,\middle|\, \begin{matrix} 1-\frac{a+1}{2} \\ \frac{a-1}{2}, \frac{1-a}{2}, -\frac{a+1}{2} \end{matrix}\right)\right] \quad (17)$$

It should be mentioned here, that the above expression (17), can be easily obtained from the corresponding expression for the gamma gamma distribution model, derived in [9].

Furthermore, by substituting (10) in (16) we conclude to the new derived expression for outage probability of an OFDM RoFSO link over atmospheric turbulence channels modeled with the NE distribution:

$$P_{out,NE} = \frac{1}{N}\sum_{n=0}^{N-1}\left[1-\exp\left(-\sqrt{\frac{CNDR_{n,th}}{[CNDR_n]_{AV}}}\right)\right] \quad (18)$$

V. NUMERICAL RESULTS

In this section we present numerical results for the average BER and outage probability metrics of the M-QAM OFDM RoFSO communication link. Thus, we assume two $CNDR_{n,th}$ values i.e. 0 and 2 dB for the receiver's sensitivity, two values for the number of the OFDM subcarriers N, i.e. 2000 and 3000, two values for the QAM signal constellation M i.e. 16 and 64, and three values for the K distribution parameter α, i.e. 3, 5 and 7. The other system's parameters that concern the operation of the optical link are the OFDM symbol duration and are fixed to the following values, T_s = 1 ms, P_t = 20dBm, L_{tot} = 20 dB, while the detector's responsivity and the load resistor are equal to 0.8 A/W and 50 Ω, respectively. The relative intensity noise is -130 dB/Hz, the absolute temperature, T_{abs}, is 300 K and the third order nonlinear parameter for the inter-modulation distortion, α_3, is 9×10^{-4}, [9], [11].

It is worth mentioning here, that the above values has been chosen because are common for such OFDM RoFSO communication systems. However, results can be obtained, using the above derived expressions for any other value of the system's parameters which can be supported by the two above mentioned distributions. Further results for other parameters values, e.g. wavelength, link length, etc, can be obtained using other distribution models such as gamma gamma, log normal, etc, [11], [15], [19].

From the figures that follow, we can conclude that the atmospheric conditions affect significantly the performance of the optical communication system. The atmospheric turbulence is modeled with K and NE distributions in order to simulate the irradiance fluctuations at the receiver which correspond to strong and saturate turbulence conditions, respectively.

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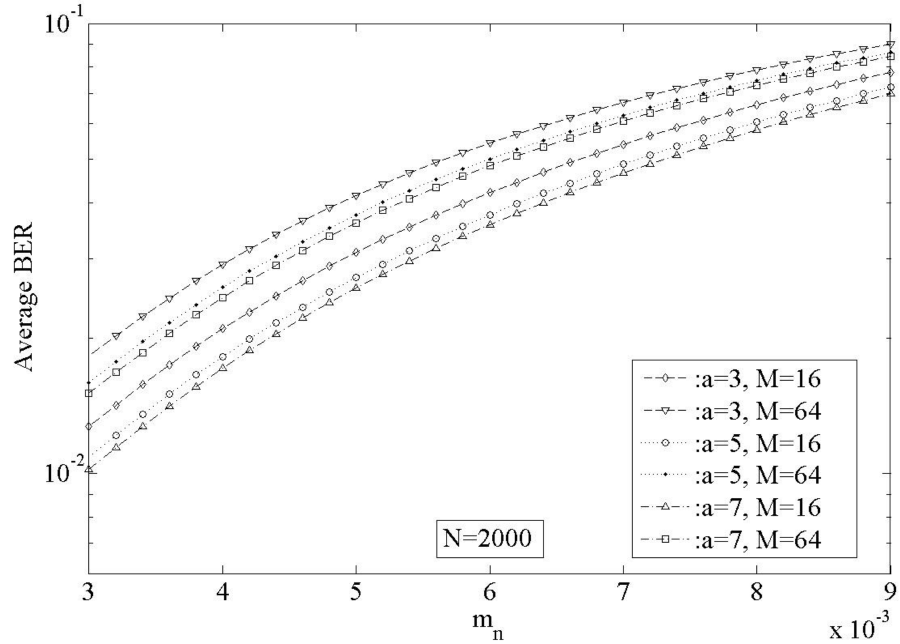

FIGURE 1. Average BER for the cases of strong turbulence conditions, i.e. using the K-distribution model.

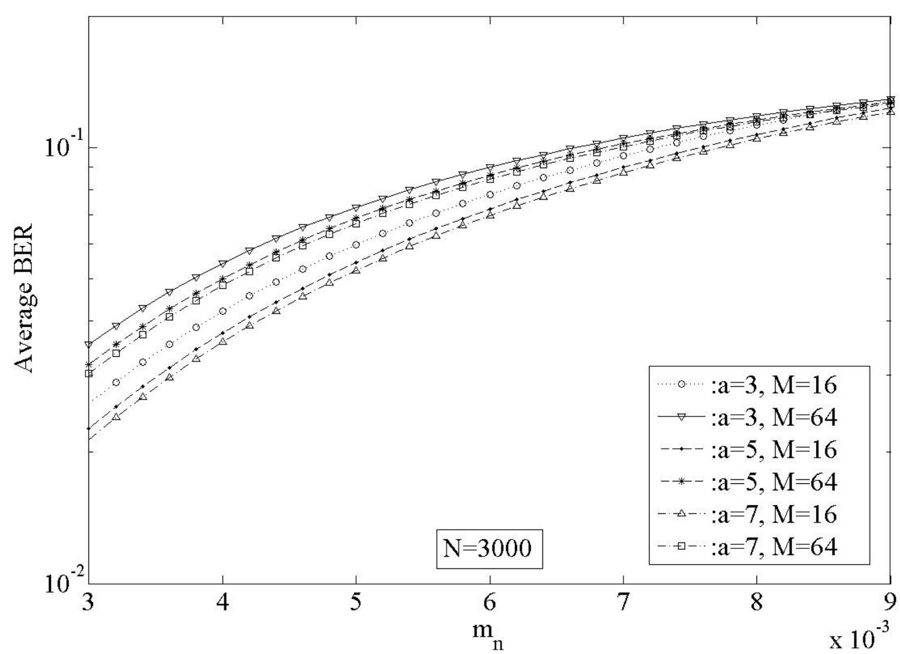

FIGURE 2. Average BER for the cases of strong turbulence conditions, i.e. using the K-distribution model.

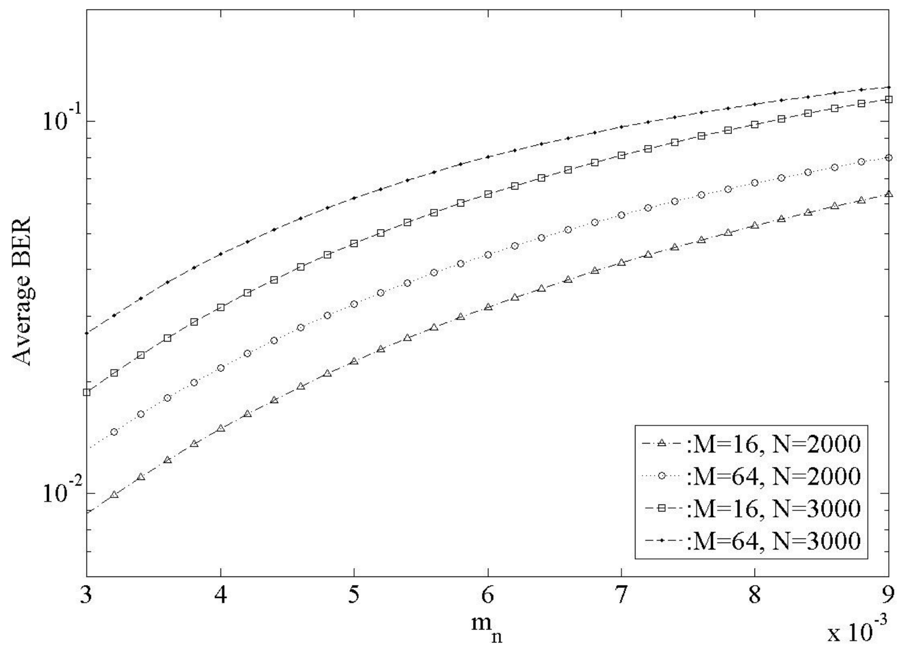

FIGURE 3. Average BER estimation for the case of atmospheric turbulence modeled with the NE distribution.

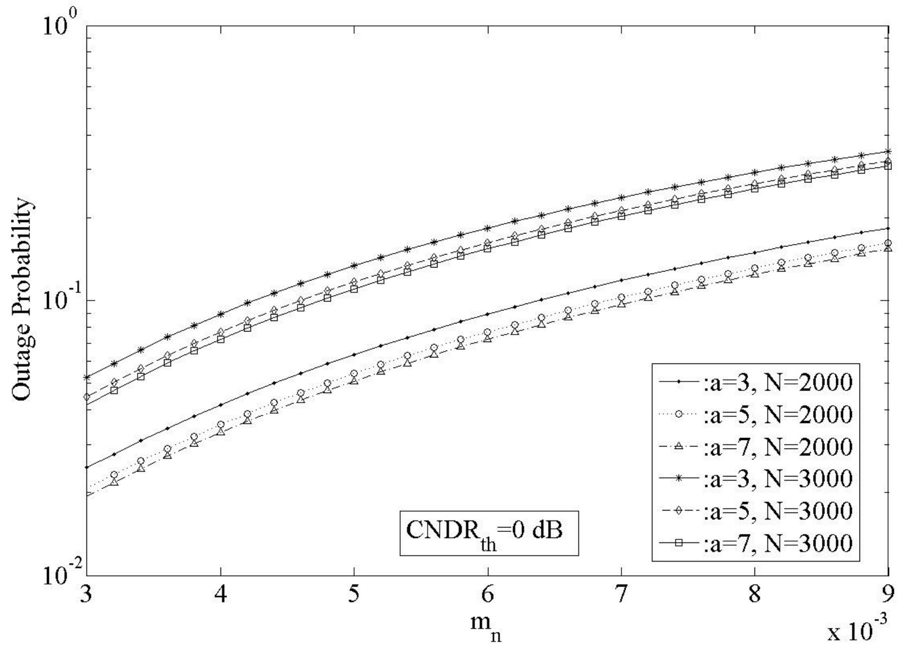

FIGURE 4. Outage Probability for the case of atmospheric turbulence modeled with the K distribution.

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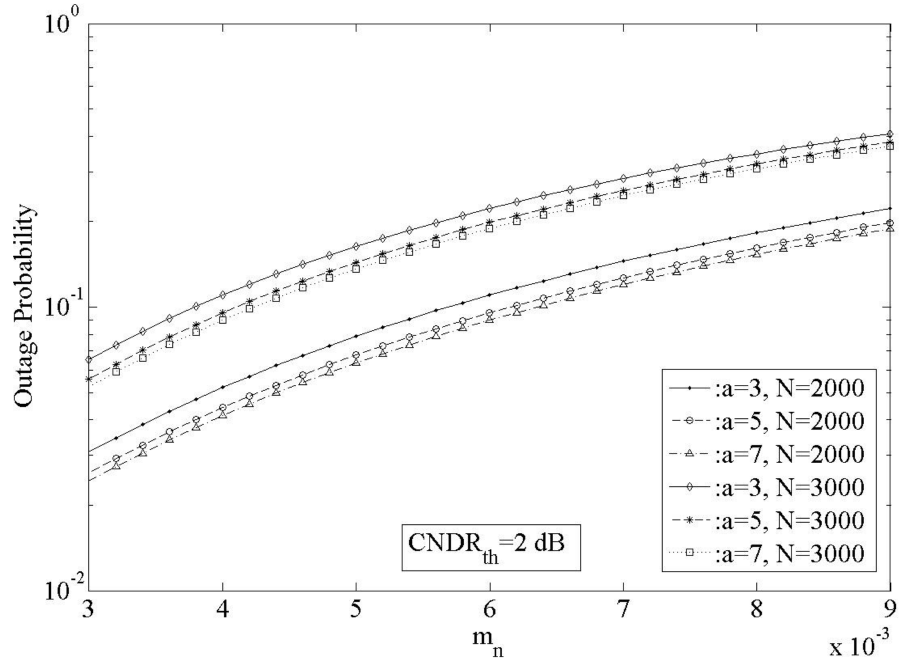

FIGURE 5. Outage Probability for the case of atmospheric turbulence modeled with the K distribution.

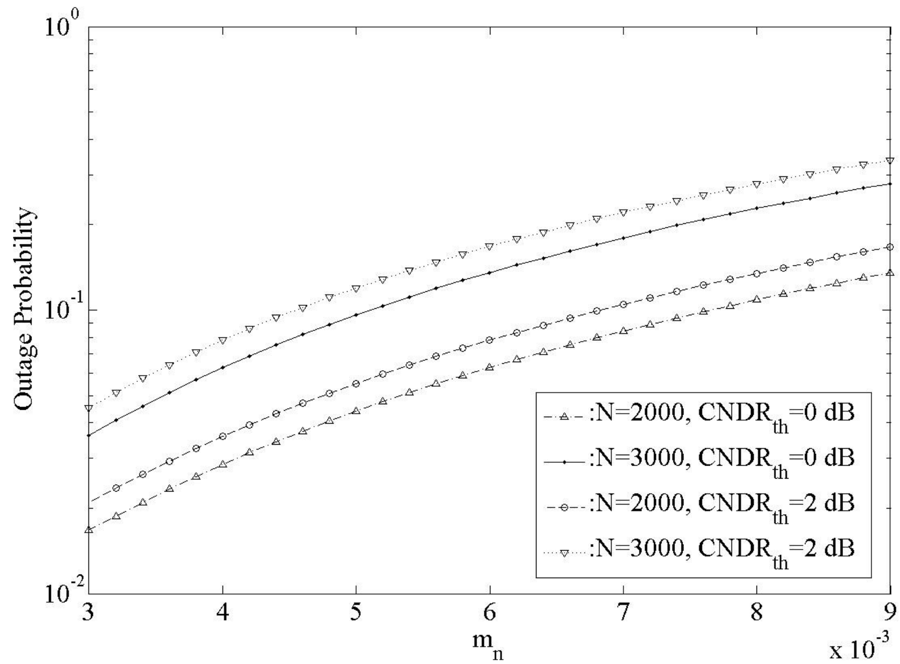

FIGURE 6. Outage Probability for the case of atmospheric turbulence modeled with the NE distribution.

VI. CONCLUSIONS

In this work we study the performance metrics of a QAM OFDM RoFSO over atmospheric turbulence channels modeled with K or the NE distribution. For this wireless optical communication system we derive closed form mathematical expressions for the estimation of the average BER and the outage probability as a function of the system's characteristics. Finally, using the derived expressions we present various numerical results for the performance of the system using common values for such communication systems.

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