BER Estimation of Dual-hop PSK OFDM RoFSO Communication System over K or NE Modeled Turbulence and Optical Fiber with Nonlinear Clipping Effect

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Abstract. Radio on free space optics (RoFSO) is a technology similar to the Radio over Fiber (RoF) communication systems, which enables the transmission of radio frequency signals (RF) in the optical domain through the free space. As a consequence, high capacity links are implemented with low operational and installation costs and without need of license for spectrum use. However, their performance depends strongly on the atmospheric conditions and the random changes of the propagation medium characteristics. On the other hand, using RoF links we can achieve higher bandwidths over longer distances but with the requirement of optical fiber infrastructure. In this work, we investigate the bit error rate (BER) performance metric of an optical communication system which consists of a RoFSO and a RoF link connected with a regenerator node. The orthogonal frequency division multiplexing (OFDM) technique is used in both links for the signal transmission with phase shift keying (PSK) format and the main mitigation factors which have been taken into account is the atmospheric turbulence effect, the nonlinear responsivity of the laser diode and the biasing with nonlinear clipping noise. Numerical results for realistic parameter values are derived concluding in a closed form mathematical expression for the estimation of system's BER.

Keywords: BER, OFDM, PSK, Fiber Optics, Free Space Optics, Nonlinear Clipping Effect.
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I. INTRODUCTION

Free Space Optics (FSO) and more specifically RoFSO is a very attractive and alternative solution in the absence of optical fiber links, for the interconnection of a central station to several remote cellular base stations. The wide variety of applications of this technology is due solely to the high bit rates, the license free spectrum, the high security level and the ease of deployment. On the other hand, their efficiency depends strongly on the weather conditions such as rain, fog, snow, atmospheric turbulence etc. and the air composition like dust, smoke and other aerosol particulate matter. All these effects increase the absorption, scattering and refractive index fluctuations of the medium, degrading the received signal quality [1]-[13].

The transmission of radio signals through optical fiber cables, simply known as radio over fiber or RoF [11], facilitates the wireless access reaching higher capacity levels with significant lower signal attenuation compared to the atmospheric path. Particularly, the total losses due to the transportation of optical signal through the fiber medium is of the order of 0.2 dB/km reducing the need of relay nodes, while for the atmospheric propagation losses range from 0.2 to more than 25 dB/km depending on the weather conditions. However, optical fiber transmission requires the availability of fiber cable infrastructure and thus augmentation of the total cost, [1]-[2].

The aforementioned effect of the atmospheric turbulence is decreasing significantly the FSO link's performance and causes the well known scintillation effect which results in irradiance fluctuations at the receiver's side. Many statistical distribution models have been proposed in order to model these signal's fluctuations according to the turbulence strength. In this work, we consider the K and negative exponential (NE) distribution models which are suitable for cases with strong and saturate atmospheric turbulence conditions, respectively [14]-[17].

OFDM is a multicarrier modulation technique which offers important benefits compared to single carrier schemes such as higher spectral efficiency, robustness against frequency selective fading and elimination of co-channel and intersymbol interference. Thus, this technique, has gained popularity in many applications, like digital subscriber lines (DSL), wireless local area networks (WLAN), advanced cellular mobile networks, etc. However, the OFDM signal exhibits high peak to average power ratios (PAPR) and is very sensitive to many nonlinear effects [18]-[24].

Thus, in this work, we present a dual hop optical communication system which consists of a RoFSO segment and a RoF link connected with a decoding and forward (DF) regenerator node. The signal propagates in each link using, the PSK modulation format for each subcarrier of the OFDM scheme. The received signal in the DF node is recognized, regenerated and retransmitted by neglecting the additive noise inserted in the first part of the whole wireless optical system. So, by considering as main mitigation factors, the atmospheric turbulence and the additive distortion of the biasing and nonlinear clipping (BAC) process for the RoF segment, we conclude to a closed form mathematical expression for the estimation of the BER of the whole relayed optical wireless and fiber communication link [11], [18]-[20].

II. AVERAGE BER FOR THE WIRELESS PART OF THE OPTICAL COMMUNICATION LINK

The optical communication system under consideration consists of two segments. For the first part, we assume a terrestrial turbulent wireless optical path between the transmitter and the

DF relay node, while an optical fiber which connects the DF node with the receiver of the whole link, stands for the second part. The information transmission is carried out by using the OFDM technique which is adopted in both links. In this multiple subcarrier modulation (MSM) scheme, the initial high data rate streams are split into lower rate parallel streams which are consequently modulated into orthogonal narrowband subcarriers, each one mapped according to a modulation format. In our case, the PSK format is chosen. The OFDM signal, after the up-conversion to the carrier frequency f_c, just before the laser diode is given as [11], [19], [20]:

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

where $\omega_n=2\pi n/T_s$, n=0,..., N-1, is the angular frequency of each orthogonal subcarrier, T_s is the duration of each OFDM symbol and X_n stands for the complex data symbol of the n_{th} subcarrier coded with Gray code mapping from a 16 and 64 PSK constellation. The transmitted optical power $P(t)$ from the laser diode LD, can mathematically be expressed with the following expression, [11], [19], [20]:

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

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 signal at the receiver of the DF node, depends strongly on the turbulence effect after and is given through the relation $P_r(t)=P(t)L_{tot}I+n(t)$, where L_{tot} stands for the total losses caused by the atmospheric propagation, $n(t)$ is the additive white Gaussian noise (AWGN) of the channel, and I represents the instantaneous normalized irradiance at the receiver which fluctuates rapidly due to the scintillation effect caused by the atmospheric turbulence phenomenon.

The atmospheric turbulence represents a significant mitigation factor for the performance of the terrestrial wireless optical links. The random spatial and temporal refractive index variations of the propagation path, cause fluctuations of the irradiance level at the receiver and cause the so-called scintillation effect. In order to estimate these intensity fluctuations, many statistical models have been proposed based on the turbulence strength. Here, we examine the cases of strong or saturate turbulence conditions which can be modeled accurately with the K or NE distribution, respectively, [14]-[17]. Thus, the probability density function (PDF) for the normalized irradiance I of the K-distribution model is given as [14], [15]:

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$$f_I(I)=\frac{2a^{\frac{a+1}{2}}}{\Gamma(a)}I^{\frac{a-1}{2}}K_{a-1}\left(2\sqrt{aI}\right) \tag{3}$$

where *Γ(.)* is the gamma function, $K_x(.)$ is the modified Bessel function of the second kind and order *x*, *α* depends on the turbulence strength, i.e. larger values of *α* correspond to weaker turbulence and *I* is the normalized irradiance. Additionally, the corresponding PDF for the NE distribution is given as, [16], [17]:

$$f_I(I)=\exp(-I) \tag{4}$$

At the photo detector (PD) of the receiver at the DF relay node, the generated current is given as, [11]:

$$i(t,I)=I_0\left[1+\sum_{n=0}^{N-1}m_n s_n(t)+a_3\left(\sum_{n=0}^{N-1}m_n s_n(t)\right)^3\right]+n_{opt}(t) \tag{5}$$

where $I_0=\rho L_{tot}P_t I$ is the dc of the received photocurrent $i(t,I)$, ρ is the PD's responsivity, while n_{opt} is the AWGN with zero mean and variance $N_0/2$, with $N_0=4K_BTF/R_L+2qI_0+I_0^2(RIN)$. In this equation, K_B is the Boltzmann's constant, *T* is the temperature, *F* is the electronic receiver amplifier noise figure, R_L is the load resistor at the PD's side, *q* is the electron charge and *RIN* stands for the relative intensity noise from the laser. Thus, the received instantaneous carrier to noise plus distortion for each subcarrier of the OFDM, $CNDR_n$, is given accurately by the following approximate formula as, [11], [19], [20]:

$$CNDR_n(I)\approx\frac{m_n^2\rho^2L_{tot}^2P_t^2I^2}{2\left([N_0/T_S]_{AV}+[\sigma_{IMD}^2]_{AV}\right)} \tag{6}$$

where the symbol $[.]_{AV}$ denotes the average value and σ^2_{IMD} stands for the inter-modulation distortion (IMD), due to the nonlinear response of the LD, which affects the specific n_{th} subcarrier among *N* equally spaced subchannels of the OFDM scheme and depends on the third order nonlinearity coefficient, a_3, and the OMI m_n, for each OFDM subcarrier [11], [19], [20]. From (4), the expected value $[CNDR_n]_{EX}$, can be estimated, considering the expected value of the normalized irradiance, *I*, i.e. *E[I]*, as, [11], [19], [20]:

$$[CNDR_n]_{EX}=\frac{(m\rho L_{tot}P_tE[I])^2}{2\left([N_0/T_s]_{AV}+[\sigma_{IMD}^2]_{AV}\right)} \tag{7}$$

The BER of a communication system is a significant metric for the estimation of its performance. For an optical OFDM communication system which is using *M*-PSK modulation format the BER is given as, [19], [20], [25]:

$$P_{b,FSO} = \frac{1}{N\log_2(M)}\sum_{n=0}^{N-1}\left\{erfc\left(\sqrt{CNDR_n(I)}\sin\left(\frac{\pi}{M}\right)\right)\right\} \tag{8}$$

where *erfc(.)* is the complementary error function and *M* is the PSK modulation format parameter.

Taking into account (8), and the PDF of the suitable distribution model, i.e. the K or the NE, the average BER for all the *N* subcarriers of the *M*-PSK OFDM RoFSO is given as [19]:

$$\left[P_{b,FSO}\right]_{AV} = \frac{1}{N\log_2(M)}\sum_{n=0}^{N-1}\int_0^\infty erfc\left(\sqrt{CNDR_n(I)}\sin\left(\frac{\pi}{M}\right)\right)f_I(I)dI \tag{9}$$

Next, by substituting in (9) the PDF of the K-distribution model, i.e. Eq. (3), we conclude to the following expression:

$$\left[P_{b,FSO}\right]_{AV,K} = \frac{2a^{\frac{a+1}{2}}}{N\Gamma(a)\log_2(M)}\sum_{n=0}^{N-1}\int_0^\infty erfc\left(\sqrt{CNDR_n(I)}\sin\left(\frac{\pi}{M}\right)\right)I^{\frac{a-1}{2}}K_{a-1}\left(2\sqrt{aI}\right)dI \tag{10}$$

while, from (9), using the PDF of the NE distribution, i.e. Eq. (4), we conclude to the following expression:

$$\left[P_{b,FSO}\right]_{AV,NE} = \frac{1}{N\log_2(M)}\sum_{n=0}^{N-1}\int_0^\infty erfc\left(\sqrt{CNDR_n(I)}\sin\left(\frac{\pi}{M}\right)\right)\exp(-I)dI \tag{11}$$

By transforming the *erfc(.)*, $K_x(.)$ and *exp(.)* functions with the corresponding Meijer functions ones, [26], the integral of (10) can be solved and we conclude to the following closed form mathematical expression for the estimation of the average BER of an M-PSK OFDM RoFSO link under strong turbulence conditions:

$$\left[P_{b,FSO}\right]_{AV,K} = \frac{N^{-1}\pi^{-\frac{3}{2}}2^{a-1}}{\Gamma(a)\log_2(M)}\sum_{n=0}^{N-1}\left\{G_{5,2}^{2,4}\left(16a^{-2}\sin^2\left(\frac{\pi}{M}\right)\left[CNDR_n\right]_{EX}\middle|\begin{matrix}\frac{1-a}{2},\frac{2-a}{2},0,\,0.5,\,1\\0,\,0.5\end{matrix}\right)\right\} \tag{12}$$

where $G_{p,q}^{m,n}[\cdot]$ stands for the Meijer-function that is a standard built in function which can be evaluated with most of the well known mathematical software packages. Furthermore, this function can be transformed to the familiar hypergeometric functions, [26].

Additionally, from (12), we estimate the following closed form mathematical expression for the estimation of the average BER of an M-PSK OFDM RoFSO link under turbulence conditions modeled with the NE distribution:

$$\left[P_{b,FSO}\right]_{AV,NE} = \frac{N^{-1}\pi^{-1}}{\log_2(M)}\sum_{n=0}^{N-1}\left\{G_{3,2}^{2,2}\left(4\sin^2\left(\frac{\pi}{M}\right)\left[CNDR_n\right]_{EX}\middle|\begin{matrix}0,\,0.5,\,1\\0,\,0.5\end{matrix}\right)\right\} \tag{13}$$

III. BER FOR THE OPTICAL FIBER PART OF THE COMMUNICATION LINK

In the second part of the optical communication system, between the DF node and the receiver, the signal propagates through an optical fiber. The OFDM scheme is used again with the same modulation format of M-PSK for each subcarrier. The OFDM signal, after the inverse fast Fourier transform (IFFT), is bipolar in general and cannot be applied directly to an intensity modulation/direct detection (IM/DD) system. Thus, a dc offset has to be added, in order to produce a suitable unipolar current to drive the laser diode and prevent the clipping of negative peaks. So, the instantaneous envelope of the OFDM signal is Gaussian distributed with mean μ_N and variance, σ_N^2. However, the high PAPR of the OFDM signal is a dominant disadvantage constrained by the finite linear response range for input amplitudes of the laser diode. During the biasing and clipping of the dc component after the FFT, a nonlinear clipping distortion insertion is inevitable. For such an optical OFDM communication system using M-PSK modulation format for optical fiber transmission including the BAC process, the total BER is expression (8) modified for this case as follows, [25]:

$$P_{b,OF} = \frac{1}{N\log_2(M)}\sum_{n=0}^{N-1}\left\{ erfc\left(\sqrt{\gamma_{e,n}}\sin\left(\frac{\pi}{M}\right)\right)\right\} \tag{14}$$

where γ_e stands for the effective SNR given as $\gamma_e = \gamma_c\gamma_d / \left[(1+\gamma_c)(1+\gamma^2)+\gamma_d\right]$, with γ_d the SNR at the receiver, γ_c the ratio of the transmitting signal, from the regenerator node, over the nonlinear clipping noise, and $\gamma = V_{DC}/\sigma_N$ is the normalized clipping level with V_{DC} being the biasing voltage. Moreover, the value of γ_c is given as [18]:

$$\gamma_c = \left[\frac{2\gamma e^{-\gamma^2/2}}{\sqrt{2\pi}}Q(\gamma) - \frac{e^{-\gamma^2}}{2\pi} - \frac{\gamma e^{-\gamma^2/2}}{\sqrt{2\pi}} + (\gamma^2+1)Q(\gamma) - (\gamma^2+1)[Q(\gamma)]^2\right]^{-1}[1-Q(\gamma)]^2 \tag{15}$$

IV. THE TOTAL AVERAGE BER OF THE WHOLE RELAYED OPTICAL LINK

The total average BER of the whole relayed optical system can be estimated through the obtained expressions in Eqs. (12)-(15). The total BER of the whole optical communication link is estimated as, [27], [28]:

$$P_{b,Total} = P_{b,OF} + [P_{b,FSO}]_{AV} - 2P_{b,OF}[P_{b,FSO}]_{AV} \tag{16}$$

Thus, for the case of strong turbulence conditions, i.e. K-distribution model, the BER of the whole relayed optical system with M-PSK OFDM RoFSO and optical fiber link with BAC process, is given by substituting (12) and (14) in (16), and we conclude to the following closed form mathematical expression:

$$P_{b,Total,turb}=\frac{1}{N\log_2(M)}\sum_{n=0}^{N-1}\Omega+\frac{N^{-1}\pi^{-\frac{3}{2}}2^{a-1}}{\Gamma(a)\log_2(M)}\sum_{n=0}^{N-1}\Psi_{turb}\left(1-2\frac{1}{N\log_2(M)}\sum_{n=0}^{N-1}\Omega\right) \tag{17}$$

where the subscript "*turb*", stands either for the NE or K-distribution model, i.e. NE or K subscript, respectively, for the atmospheric turbulence effect,

$$\Psi_K=G_{5,2}^{2,4}\left(\frac{16[CNDR_n]_{EX}}{a^2}\sin^2\left(\frac{\pi}{M}\right)\middle|\begin{matrix}\frac{1-a}{2},\frac{2-a}{2},0,0.5,1\\0,\,0.5\end{matrix}\right),\Omega=erfc\left(\sqrt{\gamma_{e,n}}\sin\left(\frac{\pi}{M}\right)\right)$$ and

$$\Psi_{NE}=G_{3,2}^{2,2}\left(4\sin^2\left(\frac{\pi}{M}\right)[CNDR_n]_{EX}\middle|\begin{matrix}0,\,0.5,\,1\\0,\,0.5\end{matrix}\right).$$

V. NUMERICAL RESULTS

In this section using expressions (12)-(14) and (17), we present the numerical results for the total average BER of the dual hop optical OFDM communication system under the K and NE turbulence, for common parameter values. The parameter value γ of the BAC process was taken equal to 6, 9 and 12 dB for optimization according to Ref. [25], while the modulation for the M-PSK format is equal to 16 and 64. The variable quantities for the estimation of the BER performance is the CNDR and SNR at the receivers of the FSO and the optical fiber link, respectively. It is obvious that these quantities can vary independently, but for simplification, here, we assume that they take the same values for both links.

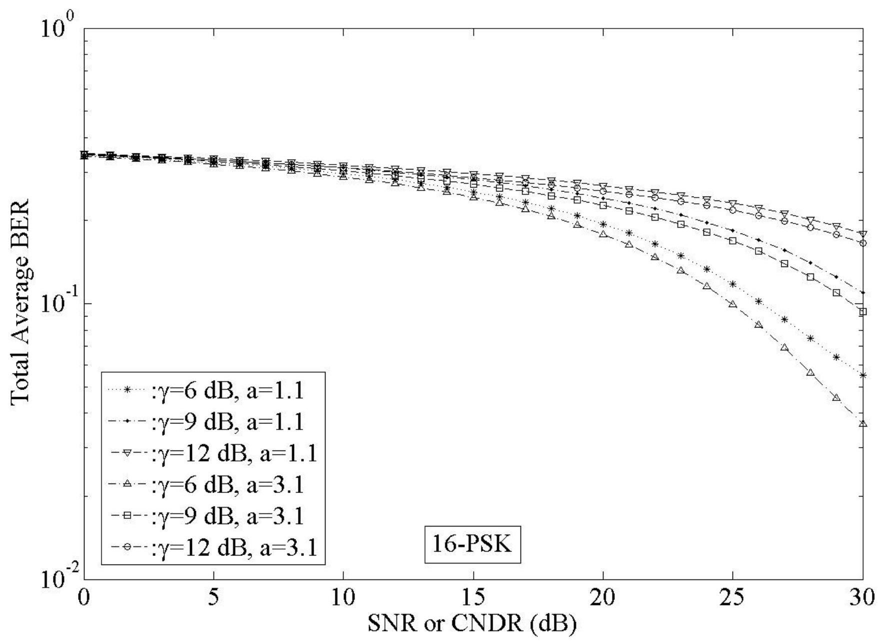

FIGURE 1. BER estimation for the 16-PSK OFDM system with K distribution.

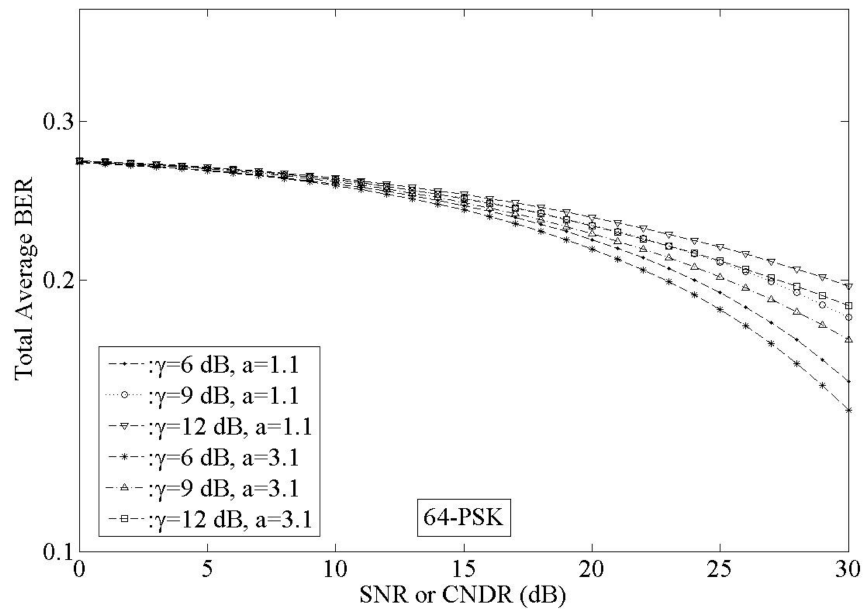

FIGURE 2. BER estimation for the 64-PSK OFDM system with K distribution.

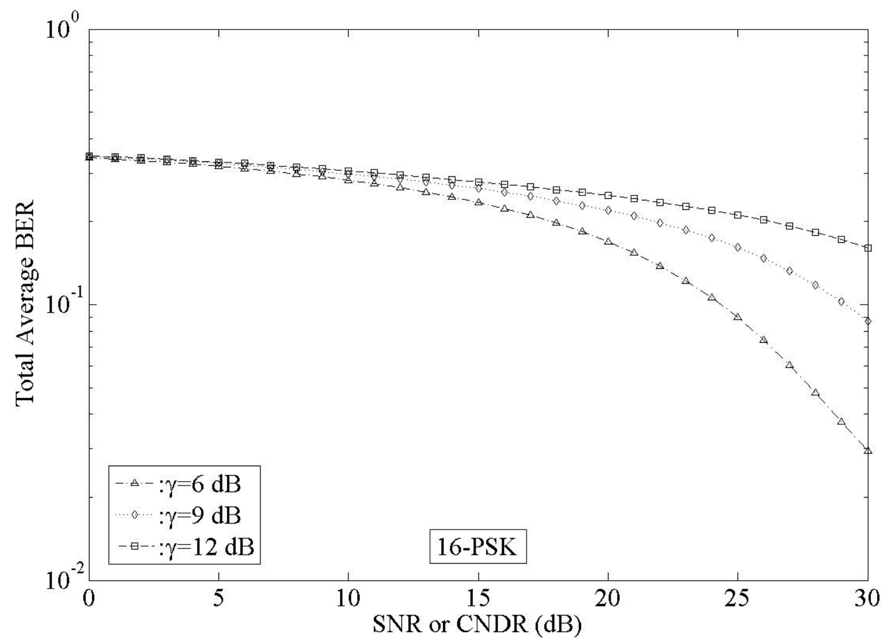

FIGURE 3. BER estimation for the 16-PSK OFDM system with NE distribution.

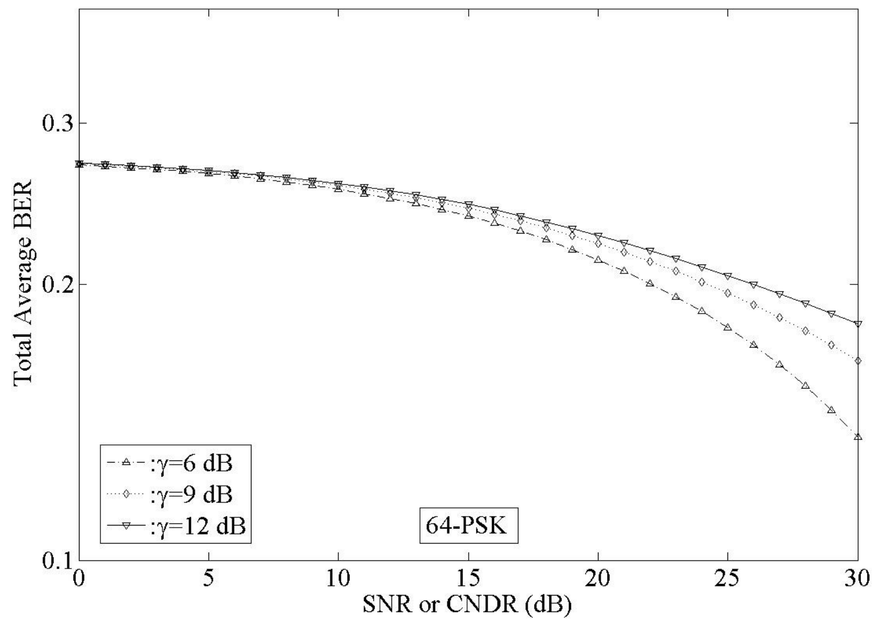

FIGURE 4. BER estimation for the 64-PSK OFDM system with NE distribution.

In Figures 1 and 2 we present the results of BER for strong turbulence conditions using the K distribution and we observe that for low SNR and CNDR values the atmospheric turbulence is the major impairment factor for the BER performance. For higher SNR and CNDR values the BAC process starting to play a significant role for the BER performance. The higher values of the BAC process parameter, conserve the BER at higher levels despite the large SNR and CNDR.

In Figures 3 and 4 we present the corresponding results for the case of saturated turbulence conditions with NE being a suitable model for such conditions. Similarly to the previous figures, we can clearly see that as parameter γ increases, the BER increases too. In all the above figures, it is also clear that for higher values of modulation format parameter M, the performance of the system becomes worse.

VI. CONCLUSIONS

In this work we studied a hybrid OFDM optical system which consists of a relayed RoFSO and RoF link which are using an M-PSK OFDM scheme. For the wireless link, we assume that the dominant performance mitigation factor is the atmospheric turbulence effect, which is modeled either with the K or NE distribution, while for the optical fiber link, the BAC process effect. For these cases we derive closed form mathematical expressions for the estimation of the average BER of each part of the optical communication link and for the whole system, as well. Finally using these expressions we present the corresponding numerical results for realistic parameter values.

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VII. REFERENCES

1. Z. Ghassemlooy, W.O. Popoola, "Terrestrial Free-Space Optical Communications", book chapter in *Mobile and Wireless Communications: Network Layer and Circuit Level Design*, S. Ait Fares and F. Adachi (Ed.), ISBN: 978-953-307-042-1, InTech, 2010.
2. H. Henniger, O. Wilfert, An Introduction to Free-Space Optical Communications, *Radioengineering*, 19, 2, 2010, 203-212.
3. W.O. Popoola, Z. Ghassemlooy, E. Leitgeb, BER and Outage Probability of DPSK Subcarrier Intensity Modulated Free Space Optics in Fully Developed Speckle, *J. of Comm.*, 4, 8, 546-554, 2009.
4. D. Tsonev, S. Sinanovic and H. Haas, Complete Modeling of Nonlinear Distortion in OFDM-Based Optical Wireless Communication, *J. Lightwave Technology*, Vol. 31, No. 18, 2013, pp. 3064-3076.
5. T. Kamalakis, T. Sphicopoulos, S. S. Muhammad, and E. Leitgeb, Estimation of the power scintillation probability density function in free-space optical links by use of multicanonical Monte Carlo sampling, *Opt. Lett.*, Vol. 31, No. 21, 2006, pp. 3077–3079.
6. W. Gappmair, S. Hranilovic, E. Leitgeb, Performance of PPM on terrestrial FSO links with turbulence and pointing errors, *IEEE Commun. Lett.*, Vol. 14, No. 5, 2010, pp. 468-470.
7. H.G. Sandalidis, Coded Free-Space Optical Links Over Strong Turbulence and Misalignment Fading Channels, *IEEE Transactions on Wireless Communications*, Vol. 59, No. 3, 2011, pp. 669-674.
8. A. Katsis, H.E. Nistazakis, and G.S. Tombras, Bayesian and frequentist estimation of the performance of free space optical channels under weak turbulence conditions, *J. Franklin Inst.*, Vol. 346, 2009, pp. 315-327.
9. W. Gappmair and S.S. Muhammad, “Error performance of PPM/Poisson channels in turbulent atmosphere with gamma-gamma distribution”, *IET Electronics Letters*, Vol. 43, No. 16, art. no. 20070901, 2007.
10. L.C. Andrews, R.L. Phillips, C.Y. Hopen, Laser beam scintillation with applications. *SPIE Optical Eng. Press*, Bellingham, WA 2006.
11. A. Bekkali, C.B. Naila, K. Kazaura, K. Wakamori, M. Matsumoto, Transmission Analysis of OFDM-Based Wireless Services Over Turbulent Radio-on-FSO Links Modeled by Gamma-Gamma Distribution, *IEEE Photonics Journal*, 2, 3, 2010, pp. 509-520.
12. H.E. Nistazakis and G.S. Tombras, On the use of wavelength and time diversity in optical wireless communication systems over gamma–gamma turbulence channels, *Optics & Laser Technology*, Vol. 44, 2012, pp. 2088–2094.
13. B. Epple, Simplified Channel Model for Simulation of Free-Space Optical Communications, *IEEE/OSA J. Opt. Commun. Netw.*, Vol. 2, No. 5, 2010, pp. 293-304.
14. H.E. Nistazakis, A.D. Tsigopoulos, M.P. Hanias, C.D. Psychogios, D. Marinos, C. Aidinis, G.S. Tombras, Estimation of Outage Capacity for Free Space Optical Links Over I-K and K Turbulent Channels, *Radioengineering*, Vol. 20, No. 2, 2011, pp. 493-498.
15. H.G. Sandalidis, T.A. Tsiftsis, Outage probability and ergodic capacity of free-space optical links over strong turbulence, *El. Lett.*, 44, 1, 2008.
16. H.E. Nistazakis, A Time-Diversity Scheme for Wireless Optical Links Over Exponentially Modeled Turbulence Channels, *Elsevier, Optik -International Journal for Light and Electron Optics*, Vol. 124, Iss. 13, 2013, pp. 1386-1391.
17. H.E. Nistazakis, V.D. Assimakopoulos, and G.S. Tombras, Performance Estimation of Free Space Optical Links Over Negative Exponential Atmospheric Turbulence Channels, *OPTIK-International Journal for Light and Electron Optics*, Vol. 122, 2011 pp. 2191-2194.
18. L. Chen, B. Krongold and J. Evans, Theoretical Characterization of Nonlinear Clipping Effects in IM/DD Optical OFDM Systems, *IEEE Transactions on Communications*, Vol. 60, 2012, No. 8.
19. H.E. Nistazakis, A.N. Stassinakis, S.S. Muhammad and G.S. Tombras, BER Estimation for Multi Hop RoFSO QAM or PSK OFDM Communication Systems Over Gamma Gamma or Exponentially Modeled Turbulence Channels, *Elsevier Optics & Laser Technology*, Vol. 64, 2014, pp. 106-112.

20. H.E. Nistazakis, A.N. Stassinakis, H.G. Sandalidis and G.S. Tombras, “QAM and PSK OFDM RoFSO over *M*-Turbulence Induced Fading Channels”, *IEEE Photonics Journal*, Vol. 7, No. 1, DOI: 10.1109/JPHOT.2014.2381670, 2015.
21. Q. Shi, Asymptotic Clipping Noise Distribution and its Impact on M-ary QAM Transmission Over Optical Fiber, *IEEE Trans. Commun.*, 43, 1995, pp. 2077-2084.
22. A. Mostafa and S. Hranilovic, In-Field Demonstration of OFDM-Over-FSO, *IEEE Photonics Technology Letters*, 24, 8, 2012, pp. 709-711.
23. S. Dimitrov, S. Sinanovic and H. Hass, Clipping Noise in OFDM-Based Optical Wireless Communication Systems, *IEEE Trans. Commun.*, Vol. 60, No. 4, 2012, pp. 1072-1081.
24. A.J. Lowery, L.B. Du and J. Armstrong, Performance of Optical OFDM in Ultralong-haul WDM Lightwave Systems, *IEEE J. Lightwave Technology*, Vol. 25, No. 1, pp. 131-138, 2007.
25. J. Proakis, Digital Communications, 4th Edition, *McGraw-Hill*, 2001.
26. V.S. Adamchik and O.I. Marichev, The Algorithm for Calculating Integrals of Hypergeometric Type Function and its Realization in Reduce System, Proc. Intl Conference on Symbolic and Algebraic Computation, Japan, 1990, pp. 212-224.
27. E. Morgado, I. Mora-Jiménez, J. J. Vinagre, J. Ramos and A.J. Caamaño, End-to-End Average BER in Multihop Wireless Networks over Fading Channels, *IEEE Transactions on Wireless Communications*, Vo. 9, 2010, No. 8.
28. H.E. Nistazakis, A.N. Stassinakis, G.S. Tombras, S.S. Muhammad and A.D. Tsigopoulos, *K Modeled Turbulence and Nonlinear Clipping for QAM OFDM with FSO and Fiber Serially Linked*, *20th International Conference on Microwaves, Radar, and Wireless Communications MIKON-2014*, *IEEE Conference Proceedings, ieeexplore.ieee.org,* ISBN: 978-1-4577-1435-1, DOI: 10.1109/MIKON.2014.6900015, 2014, pp. 1-4.

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