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OFDM Wireless Optical Communication Systems with Serial Relays Over Exponentially Modeled Turbulence Channels

A. Stassinakis, H. Nistazakis, A Tsigopoulos, and G. Tombras

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OFDM WIRELESS OPTICAL COMMUNICATION SYSTEMS WITH SERIAL RELAYS OVER EXPONENTIALLY MODELED TURBULENCE CHANNELS

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ABSTRACT

The optical wireless communication systems attract very significant research and commercial interest, the last years, due to their high availability, and performance characteristics with relatively low installation and operational cost. On the other hand, due to the fact that the optical channel which is used in this technology is the atmosphere, their performance depends strongly on the atmospheric conditions and the link's characteristics. Thus, the effective distance that these systems can cover is relatively short. Thus, in many cases where the long distance signal propagation using wireless optical systems, is necessary, relay nodes are used. In this work, we study the performance of a wireless optical system, which is using the orthogonal frequency division multiplexing (OFDM) technique and relay nodes which decode and retransmit the received signal, over atmospheric turbulence channels modeled with the negative exponential distribution. For this system, we derive closed form mathematical expressions for its outage probability and average bit error rate (BER). Finally, we present the corresponding numerical results for realistic cases with common parameter values.

KEYWORDS:
BER, Wireless Optical Communications, OFDM, Outage Probability, Decode and Forward Relay Nodes, Negative Exponential Distribution.

I. INTRODUCTION

The wireless optical communication systems attract very significant research and commercial interest due to their high performance, availability and reliability characteristics, with relatively low installation and operational cost along with the fact that these systems do not need license for their operation [1]-[6]. On the other hand, their main disadvantage stems from the fact that the propagation path for the information signal is the atmosphere and their characteristics do not remain invariable [1], [2], [6]. There are many atmospheric phenomena which affect the performance of these systems. One, very significant of them, is the atmospheric turbulence, which causes the scintillation effect which results in irradiance fluctuations at the receiver's side of the optical system. Many distribution models have been proposed in order to model the irradiance fluctuations according the turbulence strength [7]-[18].

Additionally, the wireless optical communication systems can work reliably for relatively short distances. In order to increase the system's action radius, relay nodes can be used. However, their use reduces the system's performance but the demand for longer link lengths is achieved [19]-[21].

In this work we study the performance and availability characteristics of a wireless optical link with serial relays. This link is using the orthogonal frequency multiplexing technique (OFDM), while, the relay nodes are assumed to be "decode and forward" (DF) ones. The OFDM is an effective technique for broadband communication systems [18]. It uses multiple narrow band subcarriers and thus the information data are propagated in parallel and not in serial. Each subcarrier is modulated using a specific modulation format and then they are placed in a high frequency carrier [5], [18], [22]-[27]. The main advantage of this scheme is the fact that the OFDM subcarriers are orthogonal to each other. Additionally, the distribution of the initial signal in many narrow subcarriers, decreases the data rate in each one of them and thus mitigates the influence of many, usually, catastrophic effects, [18], [27], [28].

The multihop wireless optical link under consideration consists of the transmitter, the receiver and between them, a series of DF regenerator relay nodes. Thus, the optical signal emitted from the laser diode (LD) using the OFDM technique, propagates through the turbulent atmosphere and reaches the receiver of the first DF relay node. Next, the signal, without the noise, is retransmitted by the first DF node and propagates until the second DF relay. This procedure is repeated until the signal arrives at the final receiver of the whole FSO system. More specifically, the above system is described in Fig. 1.

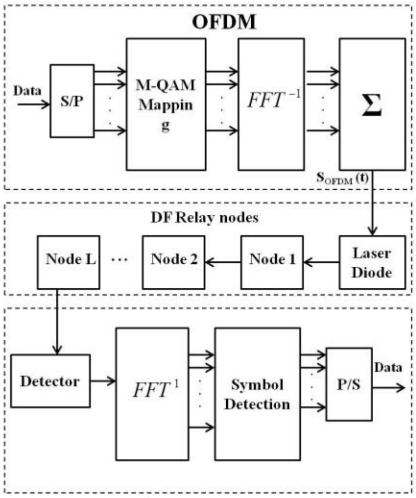

Figure 1: Block diagram for the OFDM multihop communication system, under consideration.

As mentioned above, there are many statistical distributions to model the irradiance fluctuations at each receiver's side, due to atmospheric turbulence which cause the scintillation effect. In this work we use the negative exponential, (NE), which has been proved to be suitable for strong turbulence conditions [16], [17], [29], [30]. Thus, for such an OFDM multihop wireless optical communication system over strong turbulence channels modelled with the negative exponential distribution, we derive closed form mathematical expressions for two significant metrics, the outage probability and the average BER and we present numerical results for common parameter values.

II. THE CHANNEL MODEL

In order to study the whole system's behaviour, we, first, examine the link between the system's transmitter and the receiver of the first DF node. The information signal is loaded in the N-subcarriers and thus the OFDM signal, $s_{OFDM}(t)$, after the up-conversion to the carrier frequency, f_c, just before the LD transmitter is given as [18], [25]:

$$s_{OFDM}(t)=\sum_{n=0}^{N-1}s_n(t)=\sum_{n=0}^{N-1}X_n\exp\left[i(\omega_n+2\pi f_c)t\right] \qquad (1)$$

$$for\ \ 0\le t<T_s$$

where, the quantity $\omega_n=2\pi n/T_s$, n=0,…, N-1, stands for each orthogonal frequency, T_s is the duration of the OFDM symbols and X_n is the complex symbol of the n_{th} subcarrier [18]. Depending on the modulation technique the raw data are mapped and in this work we use the M-QAM scheme with M equal to 4 or 16.

The OFDM signal modulates the optical signal of the LD transmitter and the transmitted optical power $P(t)$, is given as [18]:

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

where , P_t, is the average transmitted optical power, a_3 stands for the nonlinearity coefficient of the LD and m_n is the optical modulation index (OMI) which can be different for each frequency [18], [31], [32]. The optical signal, after the transmission, propagates through the atmosphere and reaches the receiver of the DF relay node. Thus, the optical power which arrives at the receiver's side, is given as $P_r(t)=P_t L_{tot} I+n(t)$, [18], where L_{tot} represents total losses caused by the atmosphere, $n(t)$ stands for the additive white Gaussian noise (AWGN) and I represents the instantaneous normalized irradiance at the receiver. This quantity fluctuates rapidly due to the atmospheric turbulence phenomenon which causes the scintillation effect [7]-[18]. At the receiver's output the current will be given as [18]:

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

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} represents the AWGN with zero mean and variance $N_0/2$, with $N_0=4K_B TF/R_L+2qI_0+I_0(RIN)$, [18]. In this expression, K_B is the Boltzmann's constant, T is the temperature, F is the noise figure of the receiver, R_L is the load resistor at the PD's side, q is the electron charge and RIN stand for the relative intensity noise process [18]. Thus, from (3) we conclude that the instantaneous carrier to noise plus distortion which is arriving at the receiver, for each subcarrier of the OFDM, $CNDR_n$, is given approximately as [18]:

$$CNDR_n(I)\approx\frac{m_n^2\rho^2L_{tot}^2P_t^2I^2}{2\left(\left[N_0/T_S\right]_{AV}+\left[\sigma_{IMD}^2\right]_{AV}\right)} \qquad (4)$$

where the symbol $[.]_{AV}$ stands for the average value. From (4), the average value $[CNDR_n]_{AV}$, can be estimated, by assuming that the average value of I is normalized to unity [30]. In this case is given as:

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

III. THE EXPONENTIALLY MODELED TURBULENCE CHANNEL

The scintillation effect is caused by the atmospheric turbulence. This effect mitigates significantly the performance of the wireless optical communication system due to its influence at the signal which is arriving at the PD. Thus, the atmosphere, acts as a fading channel and the signal's irradiance at the receiver fluctuates. Many statistical distributions have been proposed in order to model these irradiance fluctuations. The NE is one of them and it is suitable for cases of strong turbulence conditions [16], [17], [29], [30]. The probability density function (PDF) of this distribution, for the normalized irradiance *I*, is given as, [17]:

$$f_I(I)=\exp\left(-I\right) \quad (6)$$

and the cumulative distribution function (CDF), [17]:

$$F_I(I)=1-\exp\left(-I\right) \quad (7)$$

Using (4)-(6), with an RV transformation, the PDF for the instantaneous $CNDR_n$ is given as:

$$f_{CNDR_n}(CNDR_n)=\frac{\exp\left(-\sqrt{CNDR_n/\left[CNDR_n\right]_{AV}}\right)}{CNDR_n\left[CNDR_n\right]_{AV}} \quad (8)$$

and the corresponding CDF for the $CNDR_n$, as:

$$F_{CNDR_n}(CNDR_n)=1-\exp\left(-\sqrt{CNDR_n/\left[CNDR_n\right]_{AV}}\right) \quad (9)$$

IV. THE TOTAL OUTAGE PROBABILITY

A significant metric for the availability estimation of the wireless optical link is the outage probability [17], [18], [32], [33]. This quantity represents the probability that the instantaneous *CNDR* at the receiver falls below a specific threshold, i.e. $CNDR_{th}$, which depends on the receiver's sensitivity. More specifically the outage probability for each one of the n=1..N subcarriers of the OFDM signal for every one of the l=1..L individual optical links of the multihop system is given as [9], [18]:

$$P_{out,n,l}=\Pr\left(CNDR_{n,l}<CNDR_{n,l,th}\right)=F_{CNDR_{n,l}}\left(CNDR_{n,l,th}\right) \quad (10)$$

By substituting (9) in (10) the outage probability is:

$$P_{out,n,l}=1-\exp\left(-\sqrt{CNDR_{n,l,th}/\left[CNDR_{n,l}\right]_{AV}}\right) \quad (11)$$

Using (11), the outage probability for the OFDM wireless optical link for each individual connection, is estimated by averaging all the *N*-subcariers' probabilities of outage as:

$$P_{out,l}=\sum_{n=0}^{N-1}\frac{1-\exp\left(-\sqrt{CNDR_{n,l,th}/\left[CNDR_{n,l}\right]_{AV}}\right)}{N} \quad (12)$$

and by assuming that, $CNDR_{l,th}=CNDR_{0,l,th}= =\ldots=CNDR_{N-1,l,th}$ and $[CNDR_{l,th}]_{AV}=[CNDR_{0,l,th}]_{AV}= =\ldots=[CNDR_{N-1,l,th}]_{AV}$, Eq. (12) is simplified as:

$$P_{out,l}=1-\exp\left(-\sqrt{CNDR_{l,th}/\left[CNDR_l\right]_{AV}}\right) \quad (13)$$

In order to estimate the total outage probability for the whole OFDM multihop wireless optical link we evaluate the probability of at least one of the *L* individual links interrupts which is given as:

$$P_{out,tot}=1-\prod_{l=1}^{L}\left(1-P_{out,l}\right) \quad (14)$$

and by substituting (13) into (14) we obtain the following closed form mathematical expression for the whole OFDM multihop wireless optical link:

$$P_{out,tot}=1-\prod_{l=1}^{L}\left(\exp\left(-\sqrt{CNDR_{l,th}/\left[CNDR_l\right]_{AV}}\right)\right) \quad (15)$$

V. THE TOTAL AVERAGE BER

A significant metric for the estimation of the system's performance is the BER [32], [34]-[36]. For the average BER's estimation, we assume that the total noise included in (4), (5) is AWGN, for the *M*-QAM. Thus, the average BER of each OFDM subcarrier of the total multihop wireless optical communication system, $[P_{b,l,n}]_{AV}$, by assuming Gray-coded mapping at the transmitter's side, is [18], [34]:

$$\left[P_{b,l,n}\right]_{AV}=\frac{2\left(1-M^{-1/2}\right)}{Log_2\left(M\right)}\int_0^{\infty}erfc\left(\sqrt{\frac{3CNDR_{n,l}}{4\left(M-1\right)}}\right)f_I(I)dI \quad (16)$$

where *M* is the modulation format value for the *M*-QAM. By substituting the complementary error function, *erfc(.)*, with the Meijer G function [37], and the PDF with (7), we obtain:

$$\left[P_{b,l,n}\right]_{AV} = \frac{2\left(1-M^{-1/2}\right)}{\sqrt{\pi}Log_2(M)}\int_0^{\infty}\exp(-I)\times \times G_{1,2}^{2,0}\left(\frac{3(M-1)^{-1}\left(m_{l,n}\rho L_{tot,l}P_{t,l}I\right)^2}{4\left(\left[N_0/T_S\right]_{l,AV}+\left[\sigma_{IMD}^2\right]_{l,AV}\right)}\middle|\begin{matrix}1\\0,\,0.5\end{matrix}\right)dI \tag{17}$$

The above integral is estimated, using [37], in the following closed form mathematical expression:

$$\left[P_{b,l,n}\right]_{AV} = \frac{2\left(1-M^{-1/2}\right)}{\pi Log_2(M)}\times \times G_{3,2}^{2,2}\left(\frac{3(M-1)^{-1}\left(m_{l,n}\rho L_{tot,l}P_{t,l}\right)^2}{\left(\left[N_0/T_S\right]_{l,AV}+\left[\sigma_{IMD}^2\right]_{l,AV}\right)}\middle|\begin{matrix}0,0.5,1\\0,0.5\end{matrix}\right) \tag{18}$$

Next, by assuming that the average BER for all the N subcarriers of each individual wireless optical link, is the same, the average BER, for each link will be:

$$\left[P_{b,l}\right]_{AV} = \frac{2\left(1-M^{-1/2}\right)}{\pi Log_2(M)}G_{3,2}^{2,2}\left(\frac{6[CNDR]_{l,AV}}{(M-1)}\middle|\begin{matrix}0,0.5,1\\0,0.5\end{matrix}\right) \tag{19}$$

Subsequently, the average BER of the whole multihop wireless OFDM FSO system is estimated by the following mathematical expression [19], [21]:

$$\left[P_b\right]_{AV,tot} = \sum_{i=1}^{L}\left[\left[P_{b,i}\right]_{AV}\prod_{j=i+1}^{L}\left[1-2\left[P_{b,j}\right]_{AV}\right]\right] \tag{20}$$

Next, by substituting (19) into (20) we obtain the final closed form mathematical expression for the total average BER estimation, of the whole link:

$$\left[P_b\right]_{AV,tot} = \frac{2\left(1-M^{-1/2}\right)}{\pi Log_2(M)}\times \times\sum_{i=1}^{L}\left[G_{3,2}^{2,2}\left(\frac{6[CNDR]_{i,AV}}{(M-1)}\middle|\begin{matrix}0,0.5,1\\0,0.5\end{matrix}\right)\times \times\prod_{j=i+1}^{L}\left[1-\frac{2\left(1-M^{-1/2}\right)}{\pi Log_2(M)}G_{3,2}^{2,2}\left(\frac{6[CNDR]_{i,AV}}{(M-1)}\middle|\begin{matrix}0,0.5,1\\0,0.5\end{matrix}\right)\right]\right] \tag{21}$$

VI. RESULTS AND DISCUSSION

In this section we present numerical results for the above mentioned metrics for the whole multihop OFDM wireless optical system over strong atmospheric turbulence channels modeled with the NE distribution. We have chosen thre values for L, i.e. 2, 3, 4 and two values for M, i.e. 4 and 16.

In Figure (2), we present the average BER, as a function of the average carrier to noise plus distortion, $[CNDR_l]_{AV}$, arriving at each one of the L receivers. It is clear that as the number of relay nodes is increasing, the average BER increases, as well. On the other hand, when the modulation format value, M, is increasing, the total average BER increases too.

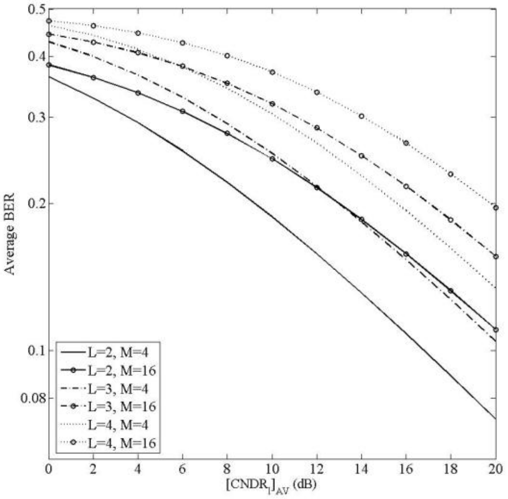

Figure 2: Average BER estimation of the multihop OFDM wireless optical link over turbulent channel, as a function of $[CNDR_l]_{AV}$, at each receiver, for three values of L, and two of M.

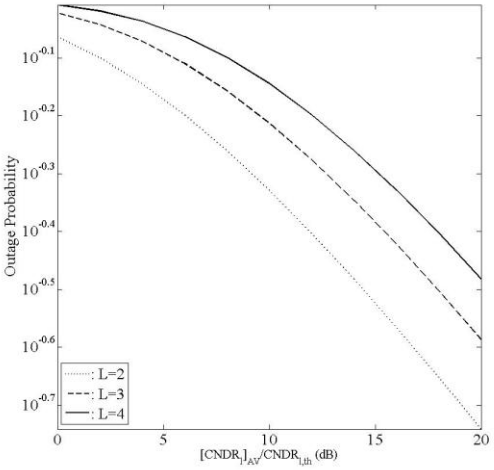

Figure 3: Outage probability estimation for OFDM wireless optical link over turbulent channel, as a function of the normalized average $[CNDR_l]_{AV}/CNDR_{l,th}$, for three values of L.

In Figure (3) we present the corresponding results for the availability of the whole multihop optical wireless OFDM system by means of its total outage probability which is estimated by the expression of Eq. (15). This metric is presented as a function of the normalized carrier to noise plus distortion, $[CNDR_l]_{AV}/CNDR_{l,th}$, at each DF receiver. Similarly with the previous case, the outage probability of the whole system is increasing as the number of relays increases.

It is worth mentioned here that the results obtained in (15) and (21), has been compared with those of [18], for the marginal case with L=1, i.e. without DF relays, and for specific turbulence strength parameter and nearly coincided.

VII. CONCLUSIONS

In this work we derived closed form mathematical expressions for the estimation of the outage probability and the average capacity of an OFDM multihop wireless optical communication system over turbulence channels modeled with the negative exponential distribution. Using these expressions, we demonstrated that the larger number of relay nodes allows long distance propagation for the wireless optical but decreases the performance and availability characteristics of the whole system. Additionally, we showed that the OFDM technique is minimizing the influence of the ISI between the subcarriers of the signal and many other performance mitigation effects, but the modulation parameter value affects significantly the system's metrics. Finally, we presented many numerical results using these expressions for various, realistic, link's parameters values.

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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, Eds S. Ait Fares and F. Adachi, ISBN: 978-953-307-042-1, InTech, 2010.

[2] H. Henniger, O. Wilfert, "An Introduction to Free Space Optical Communications", *Radioengineering*, Vol. 19, No. 2, pp. 203-212, 2010.

[3] G. Ntogari, T. Kamalakis and T. Sphicopoulos, "Performance Analysis of Space Time Block Coding Techniques for Indoor Optical Wireless Systems", IEEE Journal on Selected Areas in Communications, Vol. 27, No. 9, 2009

[4] D.K. Borah, A.C. Boucouvalas, C.C. Davis, S. Hranilovic and K. Yiannopoulos, "A Review of Communication-Oriented Optical Wireless Systems", EURASIP J. Wireless Comm. and Networking, Vol. 91, 2012.

[5] 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, pp. 3064-3076, 2013.

[6] L.C. Andrews, R.L. Phillips, C.Y. Hopen, "Laser Beam Scintillation with Applications", *SPIE Optical Engineering Press*, 2001.

[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, pp. 669-674, 2011.

[8] 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, pp. 3077–3079, 2006.

[9] 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. of the Franklin Institute*, Vol. 346, pp. 315-327, 2009.

[10] 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, pp. 468-470, 2010.

[11] 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.

[12] Md.Z. Hassan, Md.J. Hossain and J. Cheng, "Performance of Non-Adaptive and Adaptive Subcarrier Intensity Modulations in Gamma Gamma Turbulence", *IEEE Trans. Commun.*, Vol. 61, pp. 2946-2957, 2013.

[13] 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, pp. 493-498, 2011.

[14] B. Epple, "Simplified Channel Model for Simulation of Free-Space Optical Communications", *IEEE/OSA J. Opt. Commun. Netw.*, Vol. 2, No. 5, pp. 293-304, 2010.

[15] H.G. Sandalidis, "Performance Analysis of a Laser Ground-Station-to-Satellite Link With Modulated Gamma-Distributed Irradiance Fluctuations", *J. Opt. Commun. Netw.*, Vol. 2, No. 11, 2010.

[16] W.O. Popoola, Z. Ghassemlooy and V. Ahmadi, "Performance of Sub-carrier Modulated Free-Space Optical Communication Link in Negative Exponential Atmospheric Turbulence", *Int. J.*

Autonomous and Adaptive Communications Systems, Vol. 1, No. 3, pp. 342-355, 2008.

[17] H.E. Nistazakis, “A Time-Diversity Scheme for Wireless Optical Links Over Exponentially Modeled Turbulence Channels”, *OPTIK-International Journal for Light and Electron Optics*, Vol. 124, No. 13, pp. 1386-1391, 2013.

[18] A. Bekkali, C.B. Naila, K. Kazaura, K. Wakamori and M. Matsumoto, “Transmission Analysis of OFDM-Based Wireless Services Over Turbulent Radio-on-FSO Links Modeled by Gamma-Gamma Distribution”, *IEEE Photonics Journal*, Vol. 2, No. 3, pp. 509-520, 2010.

[19] M. Sheng, P. Jiang, Q. Hu, Q. Su and X.-X. Xie, “End-to-End Average BER Analysis for Multihop Free-Space Optical Communications with Pointing Errors”, *IOP Journal of Optics*, Vol. 15, Art. No. 055408, pages 7, 2013.

[20] K.P. Peppas, A.N. Stassinakis, H.E. Nistazakis and G.S. Tombras, “Capacity Analysis of Dual Amplify-and-Forward Relayed Free-Space Optical Communication Systems Over Turbulence Channels with Pointing Errors”, *J. Opt. Commun. Netw.*, Vol. 5, No. 9, 2013.

[21] 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, No. 8, 2010.

[22] Q. Shi, “Asymptotic Clipping Noise Distribution and its Impact on M-ary QAM Transmission Over Optical Fiber”, *IEEE Trans. Commun.*, Vol. 43, pp. 2077-2084, 1995.

[23] P. Banelli and S. Cacopardi, “Theoretical Analysis and Performance of OFDM Signals in Nonlinear AWGN Channels”, *IEEE Transactions on Communications*, Vol. 48, No. 3, pp. 430-441, 2000.

[24] H. Nikopour and S.H. Jamali, “On the Performance of OFDM Systems Over Cartesian Clipping Channel: A Theoretical Approach”, *IEEE Trans. on Wireless Communications*, Vol. 3, No. 6, pp. 2083-2096, 2004.

[25] A. Mostafa and S. Hranilovic, “In-Field Demonstration of OFDM-Over-FSO”, *IEEE Photonics Technology Letters*, Vol. 24, No. 8, pp. 709-711, 2012.

[26] S. Dimitrov, S. Sinanovic and H. Haas, “Clipping Noise in OFDM-Based Optical Wireless Communication Systems”, *IEEE Trans. Commun.*, Vol. 60, No. 4, pp. 1072-1081, 2012.

[27] 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, No. 8, 2012.

[28] A.N. Stassinakis, H.E. Nistazakis, K.P. Peppas, G.S. Tombras, “Improving the availability of terrestrial FSO links over log normal atmospheric turbulence channels using dispersive chirped Gaussian pulses”, *Optics & Laser Technology*, Vol. 54, pp. 329-334, 2013.

[29] A. García-Zambrana, B. Castillo-Vázquez, and C. Castillo-Vázquez, “Average Capacity of FSO Links with Transmit Laser Selection Using Non-Uniform OOK Signaling Over Exponential Atmospheric Turbulence Channels”, *Optics. Express*, Vol. 18, No. 19, pp. 20445-54, 2010.

[30] 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, pp. 2191-2194, 2011.

[31] R. Purvinskis, D. Giggenbach, H. Henniger, N. Perlot and F. David, “Multiple Wavelength Free-Space Laser Communications”, *Proc. of SPIE - The International Society for Optical Engineering*, Vol. 4975, pp. 12-19, 2003.

[32] 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, pp. 2088–2094, 2012.

[33] K. Prabu, S. Bose and D.S. Kumar, “BPSK based subcarrier intensity modulated free space optical system in combined strong atmospheric turbulence”, *Optics Communications*, Vol. 305, pp. 185-189, 2013.

[34] J. Proakis, “Digital Communications”, 4th Edition, *McGraw-Hill*, 2001.

[35] W. Liu, W. Shi, J. Cao, Y. Lv, K. Yao, S. Wang, J. Wang and X. Chi, “Bit error rate analysis with real-time pointing errors correction in free space optical communication systems”, *OPTIK*, Vol. 125, pp. 324-328, 2014.

[36] M.-S. Alouini and A.J. Goldsmith, “A Unified Approach for Calculating Error Rates of Linearly Modulated Signal Over Generalized Fading Channels”, *IEEE Trans. Commun.*, Vol. 47, No. 9, pp. 1324-1334, 1999.

[37] 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, pp. 212-224, Japan, 1990.