Modified OOK in DWDM-FSO Systems Under Atmospheric Turbulence Channel and Interchannel Crosstalk

Ebrahim E. Elsayed (✉ engebrahem16@gmail.com)

Electronics and Communications Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, El-Dakahilia Governorate, Egypt. <https://orcid.org/0000-0002-7208-2194>

Research Article

Keywords: atmospheric turbulence channel, free-space optical (FSO) communications, interchannel crosstalk, on-off keying (OOK), dense wavelength division multiplexing (DWDM) systems

Posted Date: April 26th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-460316/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

MODIFIED OOK IN DWDM-FSO SYSTEMS UNDER ATMOSPHERIC TURBULENCE CHANNEL AND INTERCHANNEL CROSSTALK

EBRAHIM E. ELSAYED

Electronics and Communications Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, El-Dakahilia Governorate, Egypt.

Author's email address: engebrahim16@gmail.com

ABSTRACT

This paper presents designing and analysis using a dense wavelength division multiplexing free-space optical (DWDM-FSO) communication systems and shows the noise effects, interchannel crosstalk, and atmospheric turbulence in the weak and strong turbulence with an on-off keying (OOK) modulation. Numerical results show error floor occurs in the DWDM-FSO link using an OOK and adaptive detection threshold.

KEYWORDS: atmospheric turbulence channel, free-space optical (FSO) communications, interchannel crosstalk, on-off keying (OOK), dense wavelength division multiplexing (DWDM) systems.

1. INTRODUCTION

Although linking communication in a dense wavelength division multiplexing free-space optical (DWDM-FSO) communication systems instead of the radio one allows ignoring license requirements, improving security, and transmitting data with broad-spectrum, it suffers from fluctuations in temperature and pressure that occur in the atmosphere regularly [1], [2]. In the case of such systems that detect directly with constant thresholds and on-off keying as well as modulate irradiance, it leads to appearing error floors at high-signal to-noise ratios (SNRs) [3], [4]. There are claims that one can avoid them through adapting the thresholds and on-off keying modulation (OOK) [5]. In the case of the limit when there is no noise when the decision threshold is continuously adapted to the changing received power (signal + crosstalk) it will be set at $\text{responsivity} \times (\text{signal average power} + \text{crosstalk average power})$ [where the average is over data but is changing depending on turbulence in either the signal case or the crosstalk case]. For that fraction of time that the crosstalk average power is bigger than the signal average power (regardless of whether it is the signal or the crosstalk's turbulence that causes this) then the data on the crosstalk wavelength is always recovered in preference to the signal data. For scintillation states within this fraction, the error probability bit-error-rate ("BER") must then be 0.5 (as signal and crosstalk data uncorrelated so crosstalk "guesses" the signal half the time). When the more usual situation that the signal average power is bigger than the crosstalk average power (regardless as to which case i.e. whether it is the signal or the crosstalk's turbulence that causes this) then the data on the signal wavelength is always recovered in preference to the crosstalk data. For individual scintillation states within this fraction of time the error probability ("BER") is then each 0. So we end up with an error floor for the average BER of $0.5 \times F + 0 \times (1-F) = F/2$ where that average is over all states of scintillation for the pdf arising from one Rytov variance and F is the fraction of time during which the crosstalk is greater than the signal. If we introduce a small amount of noise into the system, the thermal noise signal independent for simplicity that we will get deviations from this floor for lower signal powers but sufficiently high signal powers this small amount of noise can be neglected and the error floor retained. However, there is a flaw in this argumentation. Particularly, the definition of F follows that the fact that BER equals $F/2$ does not necessarily imply that BER does not depend on the received signal average power. Moreover, it is impossible to replicate the graphs with the floors they present. Specifically, in [6], the first error floor appears in Figure 2a. This illustration contains among others the dependences of BER on average received optical power in the cases that are the following: 1) there is neither interferer nor turbulence (Si); 2) there is turbulence in the signal but there is no interferer (TurbuSi); 3) there is the interferer but the turbulence is present only in the signal (TurbuSi, XT). This paper has been organized as follows. Section 2: presented system design of DWDM-FSO of 8 channels with two parts transmitter and receiver. Section 3: discusses the error floor in the case of adaptive threshold numerically. Section 4: we shed light on subtleties of an adaptive detection threshold calculation. Section 5: introduces the modified OOK modulation. Finally, section 6: show the simulation results of the quality factor and eye diagram for DWDM-FSO with non-return-to-zero (NRZ) and return-to-zero (RZ).

2. SYSTEM DESIGN

DWDM-FSO link can increase the number of channels and thus helps to enhance the technical capacity and use for long-distance data transmission. There are three types of WDM (wavelength division multiplexing) (WDM) that are commonly used: Coarse WDM (CWDM), Dense WDM (DWDM), and Broadband WDM. DWDM is a technology that multiplexes multiple optical carrier signals on a single medium by using different signals with huge channel capacity and the wavelength range from 1539 nm to 1565 nm is the most commonly located in C-Band and contribute to reducing bandwidth usage and can support capacity to reach Terabits per second and are easy to increase a data rate into the FSO [7]. Passive optical networks (PON) (i.e. the last mile connection between individual homes and companies) and the general network and gradually replace the copper-based on of network access technologies [8, 9]. WDM is the next generation of dissemination of FSO based access network which offers higher bandwidth [10, 11-14] With (WDM-PON), is set fixed wavelengths for each optical network unit (ONU), and thus more fully exploit the high transfer bandwidth available in the optical domain [12, 13]. (WDM-PON) systems offer greater security; increase bandwidth and less loss compared to time division multiple accesses (TDM/TDMA) [6-7, 14-20].

Figure. 1 Schematic representation of a DWDM using FSO link.

2.1 TRANSMITTER MODULE

In the transmitter section, we have used externally modulated transmitter in order to achieve stability. This also helps to reduce the chirps and non-linear effects [6, 15]. Here, pseudo random bit sequence (PRBS) is used to generate digital data and NRZ pulse generator is used to convert digital signal into electrical signal. After that modulator mixes the electrical signal with the light source input signal and generate optical output signal which is then sent into the multiplexer. In our design, equally spaced of 100 GHz frequency separation of eight transmitters is used starting from 1550 nm and feeder fiber length 20 km [6, 18-20].

2.2 RECEIVER MODULE

In receiver section, PIN photo-detector is connected to the output to detect the optical signal and convert it to electrical signal and send it to low pass Bessel filter which pass the low frequency signal and discard high frequency carrier signal [2, 6].

Figure. 2 Receiver scheme.

3. THE ERROR FLOOR IN THE CASE OF ADAPTIVE THRESHOLD NUMERICALLY

In what follows, we use the commonly used notations and present all values in SI units if not explicitly written otherwise. In the first case, the dependence is the following [2, 6, 18-21]:

$$BER(P_{R, sig}(1)) = \frac{1}{4} \operatorname{erfc} \left(\frac{2(r-1)RP_{R, sig}(1)/(r+1)}{2qB_e RP_{R, sig}(1) + \sigma_{th}^2} \right) \quad (1)$$

In the second one, it has the form

$$BER = \frac{1}{4} \int_0^\infty \operatorname{erfc} \left(\frac{2(r-1)R \cdot P/(r+1)}{2qB_e R \cdot P + \sigma_{th}^2} \right) P_{GG} \left(\frac{P}{P_{R, sig}(1)} \right) dP \quad (2)$$

where

$$P_{GG} \left(\frac{P}{P_{R, sig}(1)} \right) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} \left(\frac{P}{P_{R, sig}(1)} \right)^{\frac{\alpha+\beta}{2}-1} \times K_{\alpha-\beta} \left(2\sqrt{\alpha\beta \frac{P}{P_{R, sig}(1)}} \right). \quad (3)$$

Finally, in the last case the dependence is the following [6, 18-21]:

$$BER = \frac{1}{4} \int_0^\infty \operatorname{erfc} \left(\frac{2(r-1)R \cdot P(1-1/C_{XT})/(r+1)}{2qB_e R \cdot P(1+1/C_{XT}) + \sigma_{th}^2} \right) \times P_{GG} \left(\frac{P}{P_{R, sig}(1)} \right) dP. \quad (4)$$

Actually, the paper [6] is written so vaguely that it is difficult to figure out exact values of input parameters used. We believe that to replicate the graphs depicted on Figure 2a of the paper [6] under consideration that correspond to the above-mentioned cases, the following values of the input parameters written in SI units are appropriate: $R_b = 2.5 \cdot 10^9$, $m_t = 2$, $\eta = 1$, $\lambda = 1.55 \cdot 10^6$, $r = 10$, $B_0 = 60 \cdot 10^9$, $B_e = R_b/2$, $N_0 = 0$, $\sigma_{th}^2 = 98 \cdot 10^{-14}$, $l_{fso} = 1000$, $D_{RX} = 0.017$. Figure 3 depicts the results of our calculations. As one can see, there is no error floor in the case #3. Therefore, it is worthwhile to examine the adequacy of the calculations.

Figure. 3 BER versus the average received optical power (dBm) for turbulence regimes with $C_{XT} = 30$ dB,

$$C_n^2 = 1e-13m^{-2/3}.$$

4. ADAPTIVE DETECTION THRESHOLD CALCULATION

The major challenge consists in taking integrals in the right hand sides of the equations (2) and (4) properly. To find correct values for the integral limits in these equations, one should examine the dependences that are the following as written in [6, 15, 16, 18-25]:

$$p_{GG}(h_X) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} (h_X)^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta h_X}) \quad (5)$$

where h_X is the attenuation due to atmospheric turbulence [6, 18-20]

Since

$$\int_{10^{-12}}^3 p_{GG}(h_X) dh_X = 0.9725, \quad (6)$$

performing integrations in the equations (2) and (4) from $10^{-12} \cdot P_{R,sig}(1)$ to $3 \cdot P_{R,sig}(1)$ one can count on the accuracy that does not exceed a few percent. Figure 3 is the plot of the dependence of gamma-gamma probability density on h_X . On this plot h_X changes from 10^{-12} to 3. From Figure 3, it follows that on this interval there are no regions of high gradients of p_{GG} . Therefore, one can use a uniform grid performing integrations. To obtain Figure 3 we cover the range of P from $10^{-12} \cdot P_{R,sig}(1)$ to $3 \cdot P_{R,sig}(1)$ with the uniform grid that consists of 72001 nodes. To figure out whether it is enough, we perform the same calculations on the uniform grid that consists of 36001 nodes and calculate the percentage of the maximal deviation. Both in Case 2 and Case 3, the deviations are much lower than 1 %. Hence, the chosen grid is dense enough. Remarkably, conducting a numerical experiment we arrived at the dependencies of BER on average received optical power for three above mentioned cases that match the ones presented in [6] much better than Figure 3 does (see Figure 5).

Figure. 4 Attenuation due to atmospheric (h_X).

5. MODIFIED OOK

The description of the experiment is the following. One can take advantage of the uniform grid with 20001 nodes and choose for the lower limit in the integrals the value which is close to 0 whereas for the upper one the value which is much greater than the first number. For instance, one can try 10^{-12} for the lower limit and 10^{-3} for the upper one. However, the arbitrary choice of limits can lead to the normalization of the gamma-gamma probability density function that does not equal to 1 exactly. Therefore, one can introduce the normalization constant A in this function [6, 20, 21]:

$$p_{GG}\left(\frac{P}{P_{R, sig}(1)}\right) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} A \left(\frac{P}{P_{R, sig}(1)}\right)^{\frac{\alpha+\beta}{2}-1} \times K_{\alpha-\beta}\left(2\sqrt{\alpha\beta\frac{P}{P_{R, sig}(1)}}\right). \quad (7)$$

From Figure 2a of the reference [6], it follows that the values of $\log_{10}(BER)$ at the average received optical power equal to -30 dBm coincide in Cases 1 and 2. Hence, one can perform calculations assuming that the constant A presented in the equation (7) is equal to 1 and estimate its correct value as 10^Δ where Δ is equal to $\log_{10}(BER)_{P_{R, sig}(1)=-30\text{dBm}}$ in Case 1 minus such the value one obtains in Case 2 assuming that $C_n^2 = 10^{-13}$. We plotted the curve presented on Figure 3 that corresponds to Case 2 and $C_n^2 = 8.4 \cdot 10^{-15}$ using the same value of Δ . Since on Figure 5 the values of $\log_{10}(BER)$ at the average received optical power equal to -30 dBm coincide in Cases 1 and 2, one can assert that the integration limits used in the equations (2) and (4) and the increment are properly chosen. However, the drawback of this experiment consists in ignoring the degree of deviation of A from 1. Obviously, it cannot exceed few percent if one strives to obtain the curves that correspond to reality.

Figure. 5 $\log_{10}BER$ versus the average received signal optical power (dBm) for turbulence regimes with $C_{XT} = 30$ dB.

6. SIMULATION RESULTS

This part shows the simulation result for analyzing DWDM-FSO over the noises and atmospheric turbulence accentuated interchannel crosstalk [17-21]. DWDM free space optics using NRZ line codes and RZ as shown in Figure 6. This system is designed using optisystem version 7. These channels are then multiplexed using ideal multiplexer.

Initial frequency is 1550 nm and frequency spacing is 100 GHz. Modulation type are NRZ and RZ. The attenuation of the laser power in depends on two main parameters: Attenuation and Geometrical loss.

The link equation is [17, 18, 20].

$$P_{Received} = P_{Transmitted} \left(\frac{d_r^2}{d_t^2 + \theta R} \right) 10^{-\alpha \frac{R}{10}} \quad (8)$$

d_r :Receiver aperture diameter (m)

d_t :Transmitter aperture diameter (m)

θ :Beam divergence (mrad)

Figure .6 simulation eye diagrams for an eight channel of DWDM- FSO link using (a) NRZ line codes. (b) RZ line codes

TABLE. 1 PERFORMANCE ANALYSIS OF THE QUALITY FACTOR AND BER.

MODULATION TECHNIQUES	QUALITY FACTOR	BER
RZ	9.48146	8.13229e-022
NRZ	8.93394	1.97909e-019

7. CONCLUSION

This paper presented design a system model of DWDM-PON/FSO which can provide with higher bandwidth and growing demand of traffic and analyzed DWDM-FSO channel which accentuated interchannel crosstalk, interference and noises and proved that the results of numerical calculations for error floor that relies on OOK modulation and adaptive threshold false.

REFERENCES

1. V. W. S. Chan, "Free-space optical communications," *IEEE/OSA J. Lightw. Technol.*, vol. 24, no. 12, pp. 4750–4762, Dec. 2006.
2. J. H. Shapiro and R. C. Harney, "Burst-mode atmospheric optical communication," in *Proc. Nat. Telecommun. Conf.*, 1980, pp. 27.5.1–27.5.7.
3. J. Li, J. Q. Liu, and D. P. Taylor, "optical communication using subcarrier PSK intensity modulation through atmospheric turbulence channels," *IEEE Trans. Commun.*, vol. 55, no. 8, pp. 1598–1606, Aug. 2007.
4. A. Jurado-Navas, J. M. Garrido-Balsells, M. Castillo-Vazquez, and A. Puerta-Notario, "Closed-form expressions for the lower-bound performance of variable weight multiple pulse-position modulation optical links through turbulent atmospheric channels," *IET Commun.*, vol. 6, no. 4, pp. 390–397, Mar. 2012.
5. L. Yang, X. Song, J. Cheng, and J. F. Holzman, "Free-Space optical communications over lognormal fading channels using OOK with finite extinction ratios," *IEEE Access*, vol. 4, pp. 574–584, January 2016.
6. A. O. Aladeloba, M. S. Woolfson, and A. J. Phillips, "WDM FSO network with turbulence-accentuated interchannel crosstalk," *IEEE/OSA*, vol. 5, no. 6, pp. 641–651, June 2013.
7. E. Ciarabella, Y. Arimoto, G. Contestabile, M. Presi, A. D'Errico, V. Guarino, and M. Matsumoto, "1.28 terabit/s (32×40 Gbit/s) WDM transmission system for free space optical communications," *IEEE J. Sel. Areas. Commun.*, vol. 27, no. 9, pp. 1639–1645, Dec. 2009.
8. S. Karp, R. M. Gagliardi, S. E. Moran, and L. B. Stotts, *Optical Channels: Fibers, Clouds, Water and the Atmosphere*. New York: Plenum, 1988.
9. R. Ramaswami and K. N. Sivarajan, *Optical Networks—A Practical Perspective*, 2nd ed. London: Academic, 2002.
10. H. Manor and S. Arnon, "Performance of an Optical Wireless Communication System as a Function of Wavelength," *Applied Optics*, vol. 42, no. 21, pp. 4285–4294, July 2003.
11. S. Arnon, "Optical Wireless Communications," *Encyclopedia of Optical Engineering*, pp. 1866–1886, 2003.
12. N. Ansari, J. Zhang: 'Media access control and resource allocation for next generation passive optical networks' (Springer, 2013).
13. T. J. Zuo, A. J. Phillips: 'Performance of burst mode receivers for optical digital pulse position Modulation in passive optical network application', *IET Optoelectron.*, 2009, 3, (3), pp. 123–130.
14. I. T. Monroy and E. Tangdiongga, *Crosstalk in WDM Communication Networks*. Norwell, MA: Kluwer Academic, 2002.
15. L. C. Andrews, R. L. Phillips: 'Laser beam propagation through random media' (SPIE Press, Bellingham, Washington, 2005, 2nd edn.).
16. A. K. Majumdar: 'Free-space laser communication performance in the atmospheric channel', *J. Opt. Fiber Commun. Rep.*, 2005, 2, pp. 345–396.
17. H. Willebrand, and B. S. Ghuman, "Fiber Optics without Fiber," *IEEE*, 2001.
18. Scott Bloom, "Physics of free space optics," 2002.
19. E. E. Elsayed, B. B. Yousif, and M. M. Alzalabani, "Performance enhancement of the power penalty in DWDM FSO communication using DPPM and OOK modulation," *Opt. Quantum Electron.*, vol. 50, no. 7, 2018, doi: 10.1007/s11082-018-1508-y.
20. E. E. Elsayed and B. B. Yousif, "Performance enhancement of M-ary pulse-position modulation for a wavelength division multiplexing free-space optical systems impaired by interchannel crosstalk, pointing error, and ASE noise," *Opt. Commun.*, vol. 475, 2020, doi: 10.1016/j.optcom.2020.126219.
21. E. E. Elsayed and B. B. Yousif, "Performance enhancement of the average spectral efficiency using an aperture averaging and spatial-coherence diversity based on the modified-PPM modulation for MISO FSO links," *Opt. Commun.*, vol. 463, 2020, doi: 10.1016/j.optcom.2020.125463.
22. E. E. Elsayed and B. B. Yousif, "Performance evaluation and enhancement of the modified OOK based IM/DD techniques for hybrid fiber/FSO communication over WDM-PON systems," *Opt. Quantum Electron.*, vol. 52, no. 9, 2020, doi: 10.1007/s11082-020-02497-0.

23. B. B. Yousif, E. E. Elsayed, and M. M. Alzalabani, "Atmospheric turbulence mitigation using spatial mode multiplexing and modified pulse position modulation in hybrid RF/FSO orbital-angular-momentum multiplexed based on MIMO wireless communications system," *Opt. Commun.*, vol. 436, pp. 197–208, 2019, doi: 10.1016/j.optcom.2018.12.034.
24. B. B. Yousif and E. E. Elsayed, "Performance Enhancement of an Orbital-Angular-Momentum-Multiplexed Free-Space Optical Link under Atmospheric Turbulence Effects Using Spatial-Mode Multiplexing and Hybrid Diversity Based on Adaptive MIMO Equalization," *IEEE Access*, vol. 7, pp. 84401–84412, 2019, doi: 10.1109/ACCESS.2019.2924531.
25. E. E. Elsayed and B. B. Yousif, "Performance enhancement of hybrid diversity for M-ary modified pulse-position modulation and spatial modulation of MIMO-FSO systems under the atmospheric turbulence effects with geometric spreading," *Opt. Quantum Electron.*, vol. 52, no. 12, 2020, doi: 10.1007/s11082-020-02612-1.

Compliance with ethical standards

Conflict of interest: The author declares that there is no conflict of interest regarding the manuscript. The author is responsible for the content and writing of this article. The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Figures

Figure 1

Schematic representation of a DWDM using FSO link.

Figure 2

Receiver scheme.

Figure. 3 BER versus the average received optical power (dBm) for turbulence regimes with $C_{XT} = 30$ dB,
 $C_n^2 = 1e-13m^{-2/3}$.

Figure 3

Please view the figure caption in the figure.

Figure 4

Attenuation due to atmospheric (hx).

Figure 5

$\text{Log}_{10}\text{BER}$ versus the average received signal optical power (dBm) for turbulence regimes with $\text{CXT} = 30$ dB.

(a)

(b)

Figure 6

simulation eye diagrams for an eight channel of DWDM- FSO link using (a) NRZ line codes. (b) RZ line codes