An Empirical Expression for Attenuation Coefficient Evaluation of FSO Links During Night-Time Over Maritime Area of Piraeus Port in Greece

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***Abstract*— Free space optical (FSO) systems are extensively used in modern communication networks, due to the high performance and security they can achieve. However, their performance is strongly affected by the weather conditions and the various atmospheric phenomena. In this work, the influence of the atmospheric condition on an FSO system installed in maritime environment is experimentally investigated. More precisely, an empirical experimental model for the attenuation coefficient/ optical power received based on the impact of main atmospheric parameters, i.e. relative humidity, temperature, etc, will be extracted for an FSO system in the maritime environment of the port of Piraeus, during night-time. This model will be validated comparing the measured attenuation coefficient/ optical power received to the one that is estimated from the experimental model. The existence of such a model will be a very useful and important tool in the deployment of modern FSO communication networks, as the expected performance of the system will be estimated with high precision through basic atmospheric parameters of the area which can be easily estimated.**

Keywords – Free Space Optical Communications; Signal propagation; Atmospheric Losses

1. Introduction

During the last two decades, FSO systems have attracted intense interest in the field of wireless communications, due to the advantages they offer that make them a trustworthy solution in high demanding modern networks of the next generation, i.e. 5G/5G+. Their main advantages are the low operational and installation cost and the very high data rate they can achieve. On the other hand, the FSOs systems' performance strongly depends on the weather and atmospheric conditions of the atmospheric channel that are impossible to be precisely predicted. The main factor that attenuates the power of the transmitted signal is the atmospheric absorption while the atmospheric turbulence is another very important factor that degrades the beam's power. In order to investigate how these factors affect the performance of these systems, various theoretical models that describe turbulence and absorption have been developed, [1]-[7]. In order to verify the validity of such models, many experimental links have been deployed around the world investigating the performance and the availability of FSO systems under various weather and atmospheric conditions, [8]-[18]. Furthermore, experimental results are used not only for theoretical model validation but empirical models estimating accurately many performance parameters can be extracted. Such models have a great impact before deploying a new FSO system, as knowing the weather and atmospheric conditions of the area, the performance of the system can be estimated with higher accuracy than a theoretical model can provide. In this work, a horizontal terrestrial FSO link has been installed over the sea in the maritime environment of Piraeus Port in Greece in order to extract an empirical model for the experimental estimation of the influence of the attenuation as a function of the atmospheric parameters such as the relative humidity, the wind speed and the air temperature.

The remainder of this work is organized as follows: In section 2, the experimental setup is analyzed, in section 3, the theoretical background is presented, while, in section 4, the empirical model is constructed. Finally, the numerical results and the corresponding conclusions are shown in sections 5 and 6, respectively.

2. Experimental Set up

The experimental FSO link under consideration consists of two FSO transceivers. The one of them is installed at the roof of a building of the Hellenic Naval Academy at the entrance of Piraeus port while, the other one, is located at the beacon of Psyttaleia island. The optical wireless link is along a horizontal path 30 meters above the sea. The geographical layout where the FSO is installed appears in Fig 1.

However, further pictures of the link cannot be provided as the area is a military base. The total distance between the trans-receivers is 2940m and the detailed technical specifications of the experimental link are presented in Table 1 that follows.

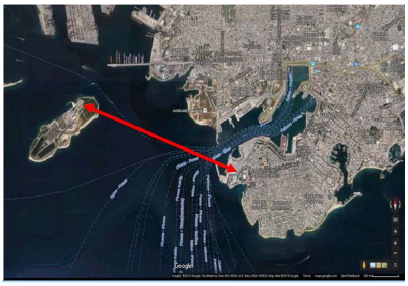

Fig. 1: Satellite view of the link

Table 1: Trans-receiver specification for the experimental FSO link.

Parameter	Values
Distance	2940m
Heigh	30m
Bit Error Rate	Less than 10^{-12} (unfaded)
Wavelength	830-860nm
Bit Rate	100Mbps
Output Power	3 Laser beams - total power 100mW
Total Power Consumption	22W
Beam Divergence	2mrad
Receiver Field of View	5 mrad
Sensitivity	-46dBm
Operating Temperature	-20°C to 50°C
Eye Safety Class	1M
Total Weight	25kg

The current that the transmitting LASER beam induces at the receiving end's photodiode, drives an electronic circuit that gives a voltage signal at its output that is proportional to the optical power of the signal, P_r, [19]. This output voltage is referred as receiver signal strength indicator (RSSI) and is recorded every 30 seconds using the link's interface management. According to the specifications of the specific optical link, the value of maximum RSSI that represents the optical power of the transmitter, P_t, is given in the technical manual.

Furthermore, a weather station that is installed at the area of the FSO link, provides accurately the necessary meteorological parameters of the area, i.e. temperature, relative humidity, wind speed, rain rate and pressure, every one minute time period.

In order to reduce the system's degrees of freedom, so as to estimate an accurate enough empirical expression, the study of this work is limited to local times between 8:00pm and before 5:00am, i.e. after the sunset and before the sunrise. This way, the influence of the sunlight radiation can be assumed as negligible.

3. The attenuation coefficient

According to Beer Lambert law, the optical power, P_r, which arrives at each receiver of the FSO link, is given through the following expression, [2],[10],[12],[13],[15],[19]:

$$\mathrm{P}_r = P_t \mathrm{e}^{-bL} \quad (1)$$

where P_t stands for the power of the transmitted optical signal, b is the attenuation coefficient and L is the FSO's link length. As mentioned above, the values of P_r and P_t are estimated through the voltage quantities U_0 and $RSSI$, respectively, [19]. Taking into account that the transmitter's optical power is set to a specific level, then the value of U_0 is constant and it can be found from link's specifications. Thus, the attenuation coefficient b can be estimated as, [10],[12],[19]:

$$b = \frac{1}{L}\ln\left(\frac{U_0}{RSSI}\right) \quad (2)$$

4. The Empirical Model for the Attenuation Evaluation

The main phenomena that affect the attenuation coefficient depend on the channel's absorption and the atmospheric turbulence effect. Thus, the value of b can be estimated as, [2],[10],[12],[13]:

$$b = b_a + b_t \quad (3)$$

with b_a being the attenuation coefficient which is proportional to the visibility and b_t represents the attenuation coefficient due to atmospheric turbulence and it can be estimated as, [14]:

$$b_t = 2\sqrt{23.17 C_n^2 k^{7/6} L^{11/6}} \quad (4)$$

where k stands for the wave number of the optical signal and C_n^2 is the refractive index structure parameter. The value of C_n^2 depends on the atmospheric and weather conditions and has been shown that it can be estimated using various theoretical or/and empirical and experimental models, [1],[10],[14].

In this work, the model of Sadot-Kopeika, [1], will be used and the refractive index structure parameter is given as, [1],[20],[21]:

$$\begin{aligned} C_n^2 &= 3.8\cdot10^{-14}W + 2\cdot10^{-15}T - 2.8\cdot10^{-15}RH + \\ &+ 2.9\cdot10^{-17}RH^2 - 1.1\cdot10^{-19}RH^3 - 2.5\cdot10^{-15}WS + \\ &+ 1.2\cdot10^{-15}WS^2 - 8.5\cdot10^{-17}WS^3 - 5.3\cdot10^{-13} \ m^{-2/3} \end{aligned} \quad (5)$$

with W being the temporal hour weight, T stands for the temperature in Kelvin degrees, RH is the relative humidity and WS represents the wind speed in m/s. All these meteorological parameters are measured in real time conditions from the installed weather station.

Furthermore, absorption is another important factor that attenuates the power of the transmitted signal. This factor strongly depends on the parameter of relative humidity, RH, [2],[8],[9], [11], [14], [15]. So the formula that can estimate the attenuation coefficient of the absorption as a function of relative humidity can be given in the form, [8],[9],[10],[15]:

$$b_a = p_1 e^{-p_2 RH} + p_3 \quad (6)$$

where p_1 is the scale parameter, p_2 is the decay parameter and p_3 is an appropriate fitting constant.

5. Experimental Results

The experiment was held between September to December of 2019, collecting measurements of RSSI and atmospheric parameters daily every 1 minute. The experimental results are taken for the time zones of [00:00 - 05:00] and [20:00 - 23:59]. The reason was to avoid the sunlight radiation in order to present an accurate enough, first experimental result. The weather is assumed to be mild so samples with wind speed higher than 6m/s and any kind of precipitations were rejected. Temperature and relative humidity has also limits due to Sadot-Kopeika turbulence model, [20],[21]. Thus, the limit values which have been taken into account are presented in Table 2.

Table 2: Limit parameter values for the experimental model

Parameter	Values
Temperature	282K - 305K
Wind Speed	<6m/s
Rain rate	0 mm/Hour
Relative Humidity	14%-92%

The measurements of wind speed, temperature, relative humidity and RSSI for all the samples of the experiment, i.e. all the days which are taking part in the experiment, are presented in Fig. 2.

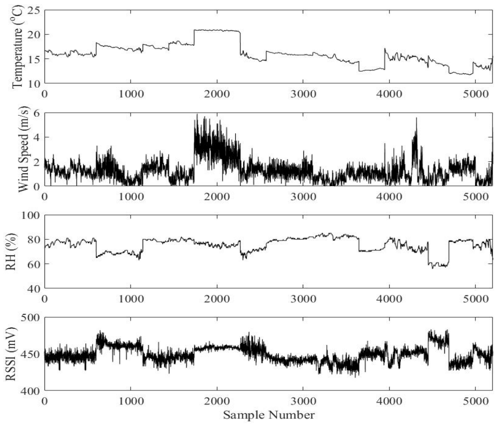

Fig.2: Temperature, Wind Speed, Relative humidity and RSSI measurements.

Then from (2), we calculate the experimental attenuation coefficient, *b*, and the results are presented in Figure (3).

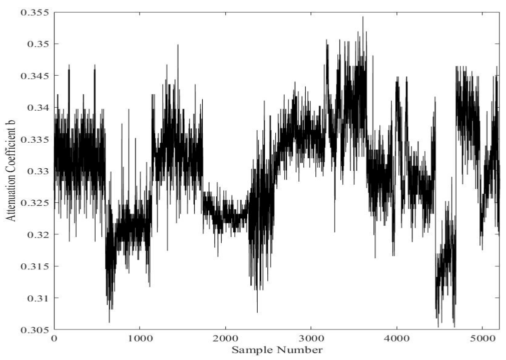

Fig. 3: Attenuation Coefficient b

Then, from (3)-(5), the empirical model for the attenuation coefficient is extracted, using the appropriate high order polynomial fitting tools. The values of the parameters of (5) that were estimated according to the best characteristics are presented in Table 3.

Table 3: Parameter values for the experimental model

Parameter	Value
p_1	0.085
p_2	0.008
p_3	0.212

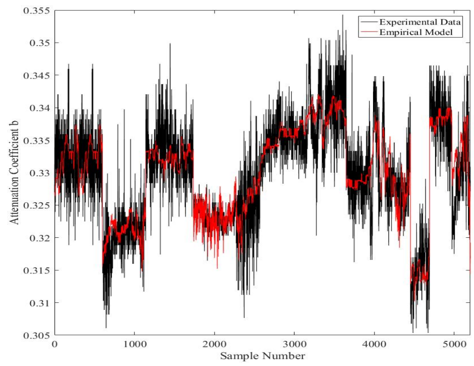

Fig. 4: Experimental data and empirical model comparison

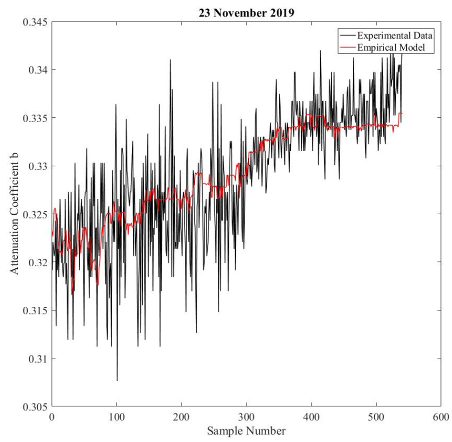

Fig. 5: Experimental data and empirical model results for 23 November 2019

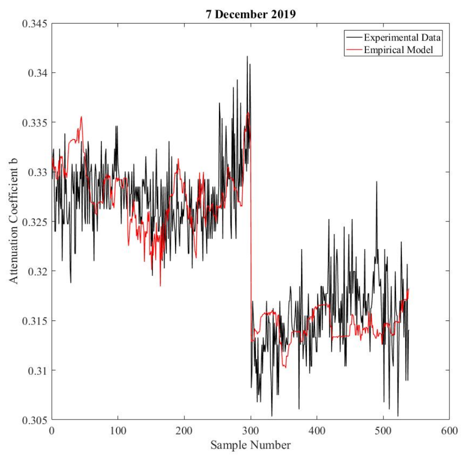

Fig. 6: Experimental data and empirical model comparison for 7 December 2019

From Figs (4), (5) and (6), it can be seen that the empirical model can describe satisfactorily the experimental results. This accuracy can be verified through the RMSE, mean and standard deviation values of Table 4, that were calculated for the whole model and for three days of the experiment, which have been chosen at random.

Table 4: RMSE results

Days	RMSE	Mean Value Exp.Data - Model	STD Exp.Data - Model
Day 1	0.0045	0.328 – 0.329	0.0069 – 0.0048
Day 2	0.0042	0.322 – 0.321	0.0073 – 0.0071
Overall	0.0044	0.324 – 0.327	0.0076 – 0.0062

6. Conclusions

In this work, an empirical model of the attenuation coefficient b was extracted for maritime environments using an FSO link at the port of Piraeus, Greece. The model that was extracted presents satisfactory accuracy for very low RMSE values. Such model can be further improved in the future as many other parameters, such as the air pollution and the presence of dust in the atmosphere, that affect the atmospheric channel, can be added in order to achieve more accurate characteristics. Additionally, in the next step, the influence of solar radiations should be taken into account in order to improve the accuracy of the model for both day-time and night-time hours.

Acknowledgment

HEN acknowledges funding from National and Kapodistrian University of Athens, Special Account of Research Grants. GDR acknowledge that this research is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Program “Human Resources Development, Education and Lifelong Learning” in the context of the project “Strengthening Human Resources Research Potential via Doctorate Research” (MIS-5000432), implemented by the State Scholarships Foundation (IKY).

References

[1] A. Arockia Bazil Raj, J. Arputha Vijaya Selvi, and S. Durairaj, "Comparison of different models for ground-level atmospheric turbulence strength (Cn^2) prediction with a new model according to local weather data for FSO applications," Appl. Opt., Vol. 54, pp. 802-815, 2015.

[2] S. Ghoname, H. A. Fayed, A. A. El Aziz and M. H. Aly, "Performance analysis of FSO communication system: Effects of fog, rain and humidity," *2016 Sixth International Conference on Digital Information Processing and Communications (ICDIPC)*, Beirut, 2016, pp. 151-155, doi: 10.1109/ICDIPC.2016.7470809

[3] H. E. Nistazakis, G. S. Tombras, A. D. Tsigopoulos, E. A. Karagianni and M. E. Fafalios, "Capacity estimation of optical wireless communication systems over moderate to strong turbulence channels," in *Journal of Communications and Networks*, vol. 11, no. 4, pp. 384-389, doi: 10.1109/JCN.2009.6391352, 2009.

[4] H. G. Sandalidis, T. A. Tsiftsis, G. K. Karagiannidis and M. Uysal, "BER Performance of FSO Links over Strong Atmospheric Turbulence Channels with Pointing Errors," in *IEEE Communications Letters*, vol. 12, no. 1, pp. 44-46, doi: 10.1109/LCOMM.2008.071408, 2008.

[5] K.P. Peppas, F. Lazarakis, A. Alexandridis and K. Dangakis, "Simple, accurate formula for the average bit error probability of multiple-input multiple-output free-space optical links over negative exponential turbulence channels," Opt. Lett., Vol. 37, pp. 3243-3245, 2012.

[6] 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, ISSN 0030-992, https://doi.org/10.1016/j.optlastec.2013.06.008, 2013.

[7] A.N. Stassinakis, H.E. Nistazakis, G.S. Tombras, "Comparative performance study of one or multiple receivers schemes for FSO links over gamma–gamma turbulence channels", Journal of Modern Optics, 59:11, 1023-1031, DOI: 10.1080/09500340.2012.697200, 2012

[8] C.H. Bang, J. Lee, Jiwoo, S.Y Hong, "Predictability Experiments of Fog and Visibility in Local Airports over Korea using the WRF Model". Journal of Korean Society for Atmospheric Environment., Vol. 24, pp. 92-101, 2008.

[9] S.A Al-Gailani, A.B. Mohammad, M.S Islam, "Tropical temperature and humidity modeling for free space otpical link". J Opt (2016) 45: 87. https://doi.org/10.1007/s12596-015-0300-7

[10] T. Hongda , Z. Zibo, J. Lihui Jiang, and S. Dongsong, "Visibility Measurement in an Atmospheric Environment Simulation Chamber," Curr. Opt. Photon., Vol. 1, pp. 186-195, 2017.

[11] H. Deng, H. Tan, F. Li, M. Cai, P.W. Chan, H. Xu, X. Huang, D. Wu, “Impact of relative humidity on visibility degradation during a haze event: A case study,Science of The Total Environment”, Vol. 569–570, pp. 1149-1158, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2016.06.190, 2016.

[12] M. Gebhart, E. Leitgeb, S.S. Muhammad, B. Flecker, C. Chlestil, M. Al Naboulsi, F. de Fornel, H. Sizun, "Measurement of light attenuation in dense fog conditions for FSO applications," Proc. SPIE 5891, Atmospheric Optical Modeling, Measurement, and Simulation, https://doi.org/10.1117/12.614830, 2005.

[13] M. Ijaz, Z. Ghassemlooy, J. Pesek, O. Fiser, H. Le Minh and E. Bentley, "Modeling of Fog and Smoke Attenuation in Free Space Optical Communications Link Under Controlled Laboratory Conditions," in *Journal of Lightwave Technology*, vol. 31, no. 11, pp. 1720-1726, doi: 10.1109/JLT.2013.2257683, 2013.

[14] J. Latal, J. Vitasek, L. Hajek, A. Vanderka, P. Koudelka, S. Kepak, V. Vašinek, “Regresion models utilization for RSSI prediction of professional FSO link with regards to atmosphere phenomena”, pp. 1-6. 10.1109/COBCOM.2016.7593514, 2016.

[15] W. G. Alheadary, Ki-Hong Park, N. Alfaraj, Y. Guo, E. Stegenburgs, T. Khee Ng, B. S. Ooi, and M. S Alouini, "Free-space optical channel characterization and experimental validation in a coastal environment," Opt. Express 26, 6614-6628, 2018.

[16] S. Rajbhandari, Z. Ghassemlooy, J. Perez, H. Le Minh, M. Ijaz, E. Leitgeb, G. Kandus, V. Kvicera, "On the study of the FSO link performance under controlled turbulence and fog atmospheric conditions," *Proceedings of the 11th International Conference on Telecommunications*, Graz, 2011, pp. 223-226.

[17] Z. Ghassemlooy, J. Perez and E. Leitgeb, "On the performance of FSO communications links under sandstorm conditions," *Proceedings of the 12th International Conference on Telecommunications*, Zagreb, 2013, pp. 53-58.

[18] M. A. Esmail, H. Fathallah and M. Alouini, "An Experimental Study of FSO Link Performance in Desert Environment," in *IEEE Communications Letters*, vol. 20, no. 9, pp. 1888-1891, doi: 10.1109/LCOMM.2016.2586043, 2016.

[19] E. M Uhlig, W. von Hoyningen-Huene, "Correlation of the atmospheric extinction coefficient with the concentration of particulate matter for measurements in a polluted urban area", Atmospheric Research, Vol. 30, Iss. 4, pp. 181-195, ISSN 0169-8095, https://doi.org/10.1016/0169-8095(93)90022-G, 1993.

[20] D. Sadot, Norman S. Kopeika, "Forecasting optical turbulence strength on the basis of macroscale meteorology and aerosols: models and validation," Opt. Eng. Vol. 31, Iss. 2, https://doi.org/10.1117/12.56059, 1992.

[21] L. Hudcova and O. Wilfert, "Prediction of atmospheric turbulence on the basis of weather conditions," *2017 Conference on Microwave Techniques (COMITE)*, Brno, pp. 1-5, doi: 10.1109/COMITE.2017.7932305, 2017.