Prospects and Challenges of Free Space Optical Communications

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Abstract. Free space optical (FSO) transmission is a technology which uses a narrow laser beam to transmit the signal from the source to the destination through the free space. Although it has various advantages, a laser beam propagating through the atmosphere is subjected to different kind of disturbances causing the attenuation of the signal and, in some extreme conditions, leading to the link outage. In fact, the atmospheric turbulences and the chemical nature of the medium is the main source of link attenuation. In this paper, we present the different challenges of FSO communications: absorption, pointing errors, atmospheric turbulence and scattering phenomenon. Moreover, based on the strength of turbulences, we will detail the FSO channel modeling. Then, we introduce some techniques to overcome the weakness presented by FSO link under different strength of atmospheric turbulences.

Keywords: Absorption · Atmospheric turbulence · Misalignment · RF

1 Introduction

Free space optical communications (FSO) have witnessed a growing interest in the last few decades due to its various advantages. In fact, FSO communications ensure secure communications using straight line to transmit data. Thus, the whole communication channel is in the visible area and any tapping activity will be detected [1]. In addition, the cost of FSO installation is low compared to the optical fiber and RF systems [2]. The FSO systems use a laser beam with a frequency in the range of Terahertz (THz). This frequency makes it able to support a large bandwidth which in turn ensures a high data rate compared to the conventional RF systems (10 to 100 Mbps) [3]. The FSO technology can be used for indoor or outdoor transmissions. Despite its various advantages, FSO communications have several limitations. FSO systems suffer from being highly sensitive to atmospheric and weather conditions. In the nature, fog is the biggest

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challenge for FSO communications [4,5,8]. In addition, fog affects the transmission where the waves are in the visible and the infrared ranges. This is due to the fact that, in these ranges, the fog's particles and the wavelength of laser beam have the same order of magnitude. Several experimental tests were made to study the influence of fog on FSO. These studies serve to characterize and measure the attenuation of the laser beam. In [6], the authors have presented several empirical models to predict the fog attenuation, then they identify the most rigorous model. They have found that the attenuation depends on the wavelength of FSO transceiver and on the visibility. On the other hand, link performances depend also on the nature and on the chemical composition of the propagation medium. The transmitted light can react with the particles presented in the atmosphere causing beam spreading, known as aerosols [7]. Hence, an interaction with the particles leads to several phenomenon that affect the link, e.g., absorption, scattering and atmospheric turbulences. Atmospheric turbulence is due to the unequal distribution of humidity and temperature in different parts of the atmosphere [8]. Several research works were conducted to investigate the effect of atmospheric turbulences on communications performances. Their studies supported by experimental tests show the effects of weather conditions and factors on the refractive index known also as the strength of atmospheric turbulences. In [9], Augustine et al. have used an experimental indoor test in order to evaluate the effects of thermal turbulence on the laser beam in term of refractive index. They have studied the fluctuation of the refractive index using the experimental data and Andrews and Phillips model. They have found that the refractive index is depending on the temperature. In [10], an experimental test of beam wander variance induced by the atmospheric turbulence has been studied. The test was made using an optical turbulence generator chamber. They confirmed that the increase of temperature gradient can cause serious impairment of FSO link. In [11], the authors made an experimental test to show the effects of harsh climate on FSO communications. They found that the temperature has the strongest effect on the link performance.

The remainder of this paper is organized as follows: In Sect. 2, we present an overview of the different source of impairments affecting the FSO communications. Then, we present the FSO channel model in Sect. 3. In Sect. 4, we introduce the different techniques used to overcome the weakness of FSO link under different strength of atmospheric conditions. Finally, Sect. 5 concludes this paper.

2 FSO Challenges

In FSO communications, laser beam is spread through the atmosphere from the transmitter to the receiver. This beam is subject of many sources of attenuation. In fact, the laser reacts with the atmosphere particles causing the attenuation of the signal. The total atmospheric attenuation is due to the scattering and to the absorption phenomena. In fact these phenomenon result from the interactions between the laser beam and the molecules of the gas and the aerosols present in the atmosphere. As given by [4,12], the aerosol is a set of particles of different forms: such as spherical or irregular. In the following, we will present the different challenges for the FSO transmissions.

2.1 Absorption

Absorption of the laser beam is caused by the interaction of the emitted photons and the molecules/atoms existing in the atmosphere (i.e., N_2, CO_2, H_2O, O_2, etc.). This interaction leads to the disappearance of some photons and their energies will be converted to heat causing an elevation of the temperature. The absorption is considered as "selective wavelength" phenomenon due to its dependence on the type of gas and its concentration in the atmosphere. The wavelength range is divided into two principal zones: Transparent and opaque zones. For, the wavelengths at the first zone, the absorption is considered minimal and it can be neglected. However, in the blocking zone, the absorption is maximal [12]. In order to overcome the effects of atmospheric absorption on laser beam propagation and taken into account that it is too difficult to control the chemical composition of the atmosphere, the FSO systems are made with wavelengths falling in the transparent zone. Thus, in the experimental work, the absorption phenomenon is neglected and the atmospheric attenuation is depending only on the scattering coefficient.

2.2 Scattering Phenomenon

Scattering phenomenon is depending on the size of aerosols and molecules present in the atmosphere. Based on the size of these particles, the scattering can be classified into Rayleigh and Mie scattering. The Rayleigh scattering appears when the particle size (r) is relatively small compared to the wavelength λ of incident beam (i.e., $r < \lambda/10$). However, the Mie scattering appears when the aerosols size are comparable to the wavelength of the transmitted light (i.e., $\lambda/10 < r < 10\lambda$). In the nature, the most known phenomenon causing scattering are fog and haze. In fact, the fog's particles and wavelength of the incident light have the same order of magnitude, reacting together leads to the apparition of Mie scattering phenomenon. In the nature, the fog appears as clouds touching the ground formed from the water vapor. In fact, when the water vapor present in the atmosphere becomes in excess, the surplus of vapor condenses. Hence, when warm and moist air flows over a colder surface the fog appears. As a result, the fog particles reduce the atmospheric visibility. The visibility is defined as the greatest distance at which an object can be clearly seen by a human observer. It is measured by the Runway Visual Range (RVP) which refers to the path length crossed by a luminous flow until its intensity is reduced to 5% of its original value.

2.3 Pointing Errors

The laser beam, transmitted by the source to the destination, is travelling in a straight line. Thus, any misalignment between the transmitter and the receiver causes pointing errors that affect the link performances. These pointing errors are mainly caused by building sways, mechanical vibrations, dynamic wind loads and thermal expansion. The effects of pointing errors on FSO transmission are considered as critical issues because these errors would increase the outage probability and bit-error rate and consequently decrease the channel capacity [13,14]. In order to mitigate the misalignment fading many techniques can be used. In fact, complex tracking mechanism can be employed to align the laser beam between the transmitter and the receiver by using a feedback channel. However, the FSO systems based on this mechanism are expensive [15]. On the other hand, for short distance, a laser beam with an increase in the power budget is considered as a suitable solution [16].

2.4 Atmospheric Turbulence

The large amount of solar irradiance absorbed by the earth surface causes an important increase of the ambient temperature and leads to the formation of warm air around the ground. This warm air passes over the surrounding air and leads to the inhomogeneity of the ambient atmosphere. This inhomogeneity is manifested by the formation of cells and eddies with different sizes and temperatures and with different refractive index [8,17,18]. The refractive index is the key factor of scintillation phenomenon caused by the atmospheric turbulence and characterizes the strength of atmospheric turbulence. In general, refractive index depends on altitude and weather factors such as temperature, solar irradiance and humidity [17,19]. The eddies react with the transmitted laser beam and cause random phase and amplitude variations of the received signal inducing distortion in the optical wave front. This phenomenon is called "scintillation" and it is responsible of the signal degradation and of the fading of the received power [20,21].

3 Channel Model

The atmospheric turbulences are random fluctuations of the intensity and the phase of the received signal. In the literature, several models are employed to explore the intensity of these fluctuations. The most used models are Log-Normal and Gamma- Gamma. In fact, for low to moderate turbulences, the fading can be modeled by Log-Normal distribution, while for moderate to strong turbulence; the fading is modeled by Gamma-Gamma distribution [13,14].

3.1 Log Normal Model

The density probability function (PDF) of Log-Normal distribution is given as follow

$$f_h\left(h\right) = \frac{1}{\sqrt{8\pi}h\sigma} \exp\left\{-\frac{\left(\ln(h) + 2\sigma^2\right)^2}{8\sigma^2}\right\} \tag{1}$$

where h is the normalized channel fading, σ is the scintillation index characterizing the strength of atmospheric turbulence.

3.2 Gamma-Gamma Model

The density probability function (PDF) of Gamma-Gamma distribution is given as follow

$$f_h\left(h\right) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} h^{\frac{(\alpha+\beta)}{2}-1} K_{\alpha-\beta}\left(2\sqrt{(\alpha\beta h)}\right), \quad (2)$$

where the parameters α and β are related to the atmospheric conditions and represent, respectively, the effective number of large and small scale eddies of the scattering process. $K_n(.)$ is the modified Bessel function of the second kind of order n and $\Gamma(.)$ denotes the Gamma function. The parameters α and β are given by [22] and denote the effective number of large and small scale eddies.

4 Techniques to Mitigate the Effect of FSO's Challenges

To bridge this gap and overcome the weakness of FSO link under strong atmospheric turbulence, several techniques are used. In the following, we will present some techniques already existed and have been tested.

4.1 Hybrid FSO/RF System

This technique consists of adding an RF link to the FSO link. This setup can exist into two configurations.

(1) *Hard switching configuration:* For the hard switching configuration, at any time only one link is active while the other link is idle. In fact, while the atmospheric conditions are favorable, the FSO is active. Otherwise, the RF will be activated and FSO goes into idle state, Fig. 1. However, the disadvantage of this approach is that the RF link can be selected for a large period and the channel capacity of FSO link is wasted.
(2) *Soft switching configuration:* In the soft switching, the two links are activated simultaneously, Fig. 2. In this configuration, the use of channel coding (i.e., Raptor codes,...) is mandatory. In fact, the data is encoded then sent through the two links. At the receiver side, the data is collected from the two links and it is stored, then decoded and interpreted.

The performances of the soft and hard switching configurations, under foggy weather, is presented in [23]. They have found that the encoded system (i.e. soft switching approach) can provide significantly higher throughput particularly in adverse weather condition than the hard switching configuration. On the other hand, the performance of soft switching configuration under harsh climate has been studied in [24]. The authors have found that the soft switching configuration under harsh and desert climate with high temperature ensures a high level of quality of service compared to the individual FSO link.

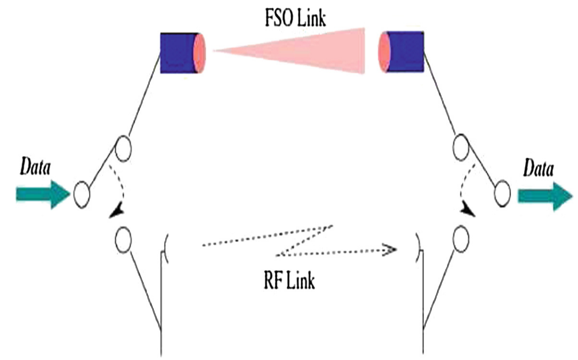

Fig. 1. Hybrid FSO/RF hard switching configuration.

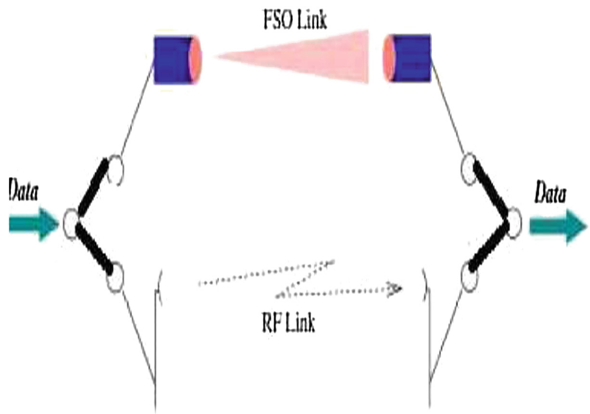

Fig. 2. Hybrid FSO/RF soft switching configuration.

4.2 Hybrid Automatic Repeat Request

In most of the recent related works, the HARQ (automatic repeat request) protocols are used on FSO communications. These protocols are used to overcome the loss of data presented under atmospheric turbulences. The main idea of HARQ is based on the acknowledgment (ACK) received from the receiver [14]. If a positive ACK is received that means that the transmitted packet was received without error. Thus, the sender will move to the next packet. However, when a negative ACK (NACK) is received, which means that an error affected the transmitted packet, a re-transmission is then required. The re-transmission process continues until a positive ACK is received or a maximum number of rounds M is achieved. Note that, the process of re-transmission depends on the type of HARQ used. In the following we will present two types of HARQ.

(1) *HARQ with incremental redundancy (HARQ-IR):* For the HARQ-IR, for each packet generated by the transmitter, a number of parity bits are added.

A positive ACK is sent in case of successful decoding. In contrary, in case of decoding failure, the erroneous packet is stored in a buffer at the receiver and a NACK is sent to the transmitter. In the second round, new parity bits are generated then sent to the receiver. This process continues until an ACK is received or M rounds are achieved. Thus, each round contains different parity bits. After each rounds, at the receiver side, a combination of all the stored parity bits is carried out which ensure a high successful decoding.

(2) *HARQ with chase combining (HARQ-CC):* In case of HARQ with Chase Combining Protocol (HARQ-CC), when a decoding failure occurs, the erroneous packet is stored in a buffer at the received side and NACK is sent to the transmitter [30]. The transmitter re-sends the same packet until an ACK is received or M rounds are achieved. At the receiver side, for each round, maximal ratio combining (MRC) is carried out to all the previous received packets.

Note that for low to moderate atmospheric turbulences, the HARQ technique can be an efficient solution to overcome the loss of data. However for strong turbulences, the loss of data increases with the strength of turbulences and the re-transmission technique becomes a useless solution. Thus, in this case using the hard or soft switching configuration can be a great solution.

5 Conclusion

In this paper, we have presented an overview of FSO communications. We have introduced the different challenges faced by a laser beam propagating through the atmosphere. These sources of attenuation can highly affect the link performances and in the worst case cause the link outage. Moreover, we have presented the FSO channel modeling for different strength of atmospheric turbulence. Then, we have presented some techniques that can be used to overcome the weakness of FSO link under different strength of atmospheric turbulence.

References

1. Gupta, A., Anand, P., Khajuria, R., Bhagat, S., Jha, R.K.: A survey of free space optical communication network channel over optical fiber cable communication. Int. J. Comput. Appl. **105**(10), 32–36 (2014)
2. Mahdy, A., Deogun, J.S.: Wireless optical communications: a survey. In: 2004 IEEE Wireless Communications and Networking Conference. WCNC 2004, vol. 4, pp. 2399–2404. IEEE (2004)
3. Kaushal, H., Kaddoum, G.: Optical communication in space: challenges and mitigation techniques. IEEE Commun. Surv. Tutor. **19**, 57–96 (2016)
4. Naboulsi, M., Sizun, H., Fornel, F.: Propagation of optical and infrared waves in the atmosphere. In: Proceedings of the Union Radio Scientifique Internationale (2005)
5. Touati, A., Abdaoui, A., Touati, F., Khandakar, A., Bouallegue, A.: Indoor test of the fog's effect on FSO link. In: Proceedings of SPIE, vol. 10096, p. 1009619-1 (2017)

6. Ijaz, M., Ghassemlooy, Z., Pesek, J., Fiser, O., Le Minh, H., Bentley, E.: Modeling of fog and smoke attenuation in free space optical communications link under controlled laboratory conditions. J. Light. Technol. **31**(11), 1720–1726 (2013)
7. Nazari, Z., Gholami, A., Vali, Z., Sedghi, M., Ghassemlooy, Z.: Experimental investigation of scintillation effect on FSO channel, Newcastle Upon Tyne, UK (2016)
8. Bendersky, S., Lilos, E., Kopeika, N.S., Blaunstein, N.: Modeling and measurements of near-ground atmospheric optical turbulence according to weather for middle east environments. In: European Symposium on Optics and Photonics for Defence and Security, pp. 350–361. International Society for Optics and Photonics (2004)
9. Augustine, S.M., Chetty, N.: Experimental verification of the turbulent effects on laser beam propagation in space. Atmósfera **27**(4), 385–401 (2014)
10. Yuksel, H.: Studies of the effects of atmospheric turbulence on free space optical communications (2005)
11. Touati, A., Abdaoui, A., Touati, F., Uysal, M., Bouallegue, A.: On the effects of temperature on the performances of FSO transmission under qatar's climate
12. Ghassemlooy, Z., Popoola, W., Rajbhandari, S.: Optical wireless communications: system and channel modelling with Matlab®. CRC Press (2012)
13. Farid, A.A., Hranilovic, S.: Outage capacity optimization for free-space optical links with pointing errors. J. Light. Technol. **25**(7), 1702–1710 (2007)
14. Trung, H.D., Pham, A.T., et al.: Pointing error effects on performance of free-space optical communication systems using SC-QAM signals over atmospheric turbulence channels. AEU-Int. J. Electron. Commun. **68**(9), 869–876 (2014)
15. Petkovic, M.I., Dordevic, G.T.: Effects of pointing errors on average capacity of FSO links over gamma-gamma turbulence channel. In: 2013 11th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services (TELSIKS) (2013)
16. Sandalidis, H.G., Tsiftsis, T.A., Karagiannidis, G.K.: Optical wireless communications with heterodyne detection over turbulence channels with pointing errors. J. Light. Technol. **27**(20), 4440–4445 (2009)
17. Leclerc, T.T., Phillips, R.L., Andrews, L.C., Wayne, D.T., Sauer, P., Crabbs, R.: Prediction of the ground-level refractive index structure parameter from the measurement of atmospheric conditions. In: SPIE Defense, Security, and Sensing, p. 76850A. International Society for Optics and Photonics (2010)
18. Sadot, D., Kopeika, N.S.: Forecasting optical turbulence strength on the basis of macroscale meteorology and aerosols: models and validation. Opt. Eng. **31**(2), 200–212 (1992)
19. Pesek, J., Fiser, O.: Research of refractive index impact on dual wavelenght FSO link attenuation. In: 2011 International Conference on Applied Electronics (AE), pp. 1–3, IEEE (2011)
20. Bendall, C.S., Frederickson, P.A., Davidson, K.L., Zeisse, C.R.: Estimating the refractive index structure parameter (Cn2) over the ocean using Bulk methods. J. Appl. Meteorol. **39**, 1770–1783 (2000)
21. Xie, G., Dang, A., Guo, H.: Effects of atmosphere dominated phase fluctuation and intensity scintillation to DPSK system. In: 2011 IEEE International Conference on Communications (ICC), pp. 1–6. IEEE (2011)
22. Lee, I.E., Ghassemlooy, Z., Ng, W.P., Uysal, M.: Performance analysis of free space optical links over turbulence and misalignment induced fading channels. In: 2012 8th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), pp. 1–6. IEEE (2012)

23. Zhang, W., Hranilovic, S., Shi, C.: Soft-switching hybrid FSO/RF links using short-length raptor codes: design and implementation. IEEE J. Sel. Areas Commun. **27**(9), 1–11 (2009)
24. Touati, A., Hussain, S.J., Touati, F., Bouallegue, A.: Effect of atmospheric turbulence on hybrid FSO/RF link availability under Qatar harsh climate. Int. J. Electr. Comput. Energ. Electron. Commun. Eng. **9**(8) (2015)
25. Chatzidiamantis, N.D., Georgiadis, L., Sandalidis, H.G., Karagiannidis, G.K.: Throughput-optimal link-layer design in power constrained hybrid OW/RF systems. IEEE J. Sel. Areas Commun. **33**(9), 1972–1984 (2015)