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RESEARCH ARTICLE

Effect of clear atmospheric turbulence on quality of free space optical communications in Yemen

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Abstract Free space optical (FSO) communication is one of the most recently developed modes of wireless communication. FSO is a technique used to convey data carried by a laser beam through the atmosphere. While FSO offers a broadband service, it requires a line of sight communication between the transmitter and receiver. The atmosphere has effects on the laser beam passing through it. For instance, the quality of data received is affected by the scattering and atmospheric turbulence. The atmospheric turbulence is caused by both temporary and special random fluctuations of the refractive index along the optical propagation path. Clear air turbulence impairs the performance of the FSO due to the fluctuation in the intensity of the laser beam. By referring to the two criteria, namely bit error rate (BER) and signal to noise ratio (SNR), this work includes analysis of the effect of atmospheric turbulence on FSO systems in Yemen by using an appropriate model.

Keywords atmospheric turbulence, scintillation, refractive index, free space optical (FSO) communication system, bit error rate (BER), signal to noise ratio (SNR)

1 Introduction

Free space optical (FSO) communication systems have many advantages when compared with the free space radio frequency based systems. These include large bandwidth, fast deployment, being license-free, having low power consumption, enhanced security and insensitivity to interference, being light weight, and having reduced size [1,2]. In free-space optics, the light-wave propagates through the atmosphere channel. The atmosphere is considered a challenging dynamical channel for electromagnetic wave propagation. Since the atmosphere channel through which light propagates is not ideal, it affects the optical carrier wave due to interaction with the atmosphere which causes various optical phenomena, such as absorption, scattering, beam-offset, beam-tilt, wavefront distortion, beam broadening, and far field speckles, depending on the atmospheric condition. However, in a clear atmosphere, with a typical attenuation coefficient of 0.43 dB/km, a major challenge facing FSO communication systems is the effect of turbulence induced irradiance fluctuation on the system performance especially for a link range exceeding 1 km [2]. Atmospheric turbulence is caused by both spatial and temporal random fluctuations of the refractive index due to temperature, pressure, and wind variations along the optical propagation path through the channel [3,4]. Atmospheric turbulence primarily causes phase shifts of the propagating optical signals resulting in distortions in the wavefront. These distortions, referred to as optical aberrations, result also in intensity distortions, referred to as scintillation.

Several works have studied the turbulence on the bit error ratio (BER) and signal to noise ratio (SNR) [5,6]. The present work aims at determining the effect of atmospheric turbulence on FSO communication in Yemen at three different intensities, namely strong, medium, and weak turbulence, for different wavelengths, namely 780, 850, and 1550 nm. We present simulation results to validate our approach. Two criteria are used to evaluate our method, namely BER and SNR.

Much work has been done toward developing the effect of clear atmospheric turbulence on the quality of FSO. The scientific meaning of this research includes transmission capabilities, a variety of applications, for example in urban areas, university campuses, and disaster zones, and where distances are short and line-of-sight is relatively inexpensive. In fact, each country is characterized by its atmospheric turbulence so that to exploit FSO technology

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this effect should be studied to have a clear image before installation.

The remainder of this paper is organized as follows: in Sect. 2, we outline the atmospheric turbulence channel modeling. In fact, we introduce the refractive index structure, scintillation, and beam spreading. In Sect. 3, we present performance criteria used to evaluate our work. In Sect. 4, simulation results and discussion are introduced. Finally, Sect. 5 presents some concluding remarks.

2 Atmospheric turbulence channel modeling

Clear air turbulence phenomena affect the propagation of optical beams because the refractive index randomly varies in space and time. Moisture, aerosols, temperature and pressure changes produce refractive index variations in the air [7]. These variations are referred to in fluid dynamics as eddies. In the context of geometrical optics, these eddies may be thought of as lenses that randomly refract the optical wavefront, producing, therefore, a distorted intensity profile at the receiver of a communication system. The intensity fluctuations are called scintillations and are one of the most important factors limiting the performance of an atmospheric FSO communication link. The most widely accepted theory of turbulence is attributed to Kolmogorov [8,9]. This theory assumes that the kinetic energy of large turbulent eddies is redistributed without loss to eddies of decreasing size until it is finally dissipated by viscosity. The refractive index varies randomly across the different turbulent eddies, leading to phase and amplitude variations inside the wavefront. Turbulence may also cause the random drifts of optical beams, a phenomenon usually referred to as wandering, and may induce beam focusing [10].

2.1 Refractive index structure

Refractive index structure parameter C_{n}^2 is the most significant parameter that determines the turbulence strength. Clearly, C_{n}^2 depends on the geographical location, altitude, and time of the day. Close to ground, there exists the largest gradient of temperature associated with the largest values of atmospheric pressure. Therefore, one should expect larger values of C_{n}^2 at sea level. As the altitude increases, the temperature gradient decreases, resulting in smaller values of C_{n}^2 [11]. The refractive-index structure constant C_{n}^2 is a measure of the strength of the fluctuations in the refractive index. Values of C_{n}^2 typically range from $10^{-15}\,\mathrm{m}^{-2/3}$ (low turbulence) in the upper atmosphere up to $10^{-13}\,\mathrm{m}^{-2/3}$ (high turbulence) near the ground [12]. In applications involving a horizontal path even over a reasonably long distance, one can assume C_{n}^2 to be quasi constant. However, a number of parametric models have been formulated to describe the C_{n}^2 profile. One of the commonly used models is the Hufnagel-Valley model [13], given by

$$C_{\mathrm{n}}^2 = 0.00594\left(\frac{v}{27}\right)^2(10^{-5}h)^{10}\exp\left(-\frac{h}{1000}\right) + 2.7 \times 10^{-16}\exp\left(-\frac{h}{1500}\right) + A_0\exp\left(-\frac{h}{100}\right), \tag{1}$$

where h is the altitude in m, v is the wind speed at high altitude (m/s), A_0 is the turbulence strength at the ground level practically, and $A_0 = 1.7 \times 10^{-14}\ \mathrm{m}^{-2/3}$.

The most important variables in its change are the wind and altitude. The higher the altitude the colder and less dense the air gets, so the turbulence level is lower [14].

2.2 Scintillation

Scintillation may be the most noticeable effect on FSO systems [15]. Light traveling through scintillation will experience intensity fluctuations, even over relatively short propagation paths. The scintillation index σ_{i}^2 describes such intensity fluctuation as the normalized variance of the intensity fluctuations expressed as follows [11]:

$$\sigma_{\mathrm{i}}^2 = \frac{\langle (I-\langle I\rangle)^2\rangle}{\langle I\rangle^2} = \frac{\langle I^2\rangle}{\langle I\rangle^2} - 1, \tag{2}$$

where $I = |E|^2$ is the signal irradiance (or intensity).

The strength of scintillation can be measured in terms of the variance of the beam amplitude or irradiance σ_{i} given by the following relationship:

$$\sigma_{\mathrm{i}}^2 = 1.23 C_{\mathrm{n}}^2 k^{7/6} l^{11/6}, \tag{3}$$

where C_{n}^2 is the refractive index structure, $k=2\pi/\lambda$ is the wave number (an expression suggesting that longer wavelengths experience a smaller variance), and l is the link range (m).

2.3 Beam spreading

Beam spreading describes the broadening of the beam size at a target beyond the expected limit due to diffraction as the beam propagates in the turbulent atmosphere. Here, we describe the case of beam spreading for a Gaussian beam, at a distance l from the source, when the turbulence is present [16]. To quantify the amount of beam spreading [16] describes the effective beam waist average as

$$\omega_{\mathrm{eff}}(l)^2 = \omega(l)^2\left\{1 + 1.33\sigma_{\mathrm{i}}^2\left[\frac{2l}{k\omega(l)^2}\right]^{5/6}\right\}, \tag{4}$$

where $\omega(l)$ is the beam waist at a propagation distance l:

$$\omega(l)^2 = \left[\omega_0^2 + \left(\frac{2l}{k\omega_0}\right)^2\right] \ (\mathrm{m}^2), \tag{5}$$

where ω_0 is the initial beam waist at $l = 0$, and $\omega_{\mathrm{eff}}(l)^2$ is the spreading of the beam caused by the turbulence. The latter describes the variation of the beam irradiance averaged over the long-term. As seen in other turbulence figures of merit, $\omega_{\mathrm{eff}}(l)^2$ depends on the turbulence strength and beam path [16]. Since $\omega_{\mathrm{eff}}(l) > \omega(l)$, the beam will experience a loss at the beam center:

$$L_{\mathrm{BE}} = 20\log_{10}\frac{\omega(l)}{\omega_{\mathrm{eff}}(l)} \ (\mathrm{dB}). \tag{6}$$

In this paper, we neglect all other noise sources, and assume that the only main noise source is the atmospheric turbulence.

3 BER and SNR

Both SNR and BER are used to assess the quality of communication systems. BER performance depends on the average received power, the scintillation strength, and the receiver noise. With an appropriate design of aperture averaging, the received optical power could be increased and the effect of the scintillation can be dumped. With turbulence, the SNR is expressed as follows [2]:

$$\mathrm{SNR} = \left(0.31C_{\mathrm{n}}^2k^{7/6}l^{11/6}\right)^{-1}. \tag{7}$$

For FSO links with an on off keying modulation scheme the BER can be written as [17]

$$\mathrm{BER} = \frac{\exp(-\mathrm{SNR}/2)}{(2\pi\mathrm{SNR})^{0.5}}. \tag{8}$$

In our model, we have assumed that the surface area of the photo detector is large enough so that the effective SNR includes the beam spreading effect, thus the effective SNR is defined as [9,18,19]

$$\mathrm{SNR}_{\mathrm{eff}} = \frac{\mathrm{SNR}}{1 + 1.33\sigma_{\mathrm{i}}^2\left[\dfrac{2l}{k\omega(l)^2}\right]^{5/6}}. \tag{9}$$

4 Simulation results and discussion

The data was taken from the Civil Aviation and Meteorology Authority and the Yemen Meteorological Service. The work includes the analysis of these real data. The purpose here is to discuss the relationship for calculating the variance, SNR, and BER for a range of parameters. We used the wavelengths of 850, 1000, and 1550 nm. Particular attention was given to the 1550 nm wavelength since it is commonly used as the 3rd window of optical communication backbone links. Moreover, being significantly bigger than visible wavelengths, the human retina in particular and the components of the eye in general are less sensitive to the 1550 nm wavelength. Thus, this wavelength is appropriate for eye safety.

Figure 1 illustrates the log intensity fluctuations versus the link range between transmitter and receiver for three values of wavelengths. The log intensity fluctuation depends on the wavelength and increases with the propagation distance. As the transmission range increases the variance (atmospheric turbulence) increases too. For a 2000 m transmission range, the variance is about 0.17 for the wavelength of 850 nm, 0.12 for 1000 nm, and 0.075 for 1550 nm. For a 4000 m transmission range, the variance is about 0.56 for 850 nm, 0.42 for 1000 nm, and 0.25 for 1550 nm. These results show that the use of a wavelength of 1550 nm can reduce the variance "atmospheric turbulence" effect on the FSO systems.

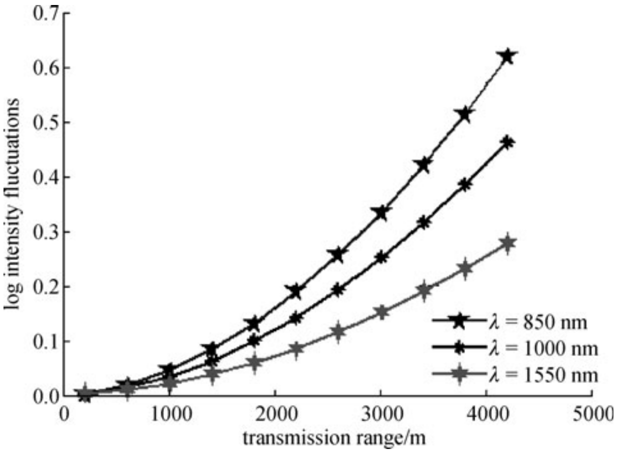

Fig. 1 Intensity fluctuations against transmission range

Figure 2 indicates the comparison between the beam spreading on a distance l from the transmitter in case of atmospheric turbulence and in case without atmospheric turbulence. The spot size of the beam at the transmitter (with the distance $l = 0$) equals 0.008 m. At the distance 200 m, the spot size of the beam is $\omega(l) = 0.015$ m in case of absent turbulence and $\omega_{\mathrm{eff}}(l) = 0.015$ m in case of turbulences. At the distance 5000 m, the $\omega(l) = 0.31$ m and $\omega_{\mathrm{eff}}(l) = 0.33$ m. From the above results, we conclude that the expansion of the spot size of the beam depends on the distance between sender and receiver as indicated on Fig. 2, and on the atmospheric turbulence along the transmission range as indicated on Fig. 3. The higher the turbulence is, the greater the expansion of the beam size is.

Figure 4 shows the SNR versus the transmission range of 0 to 4500 m. As the link range between the transmitter

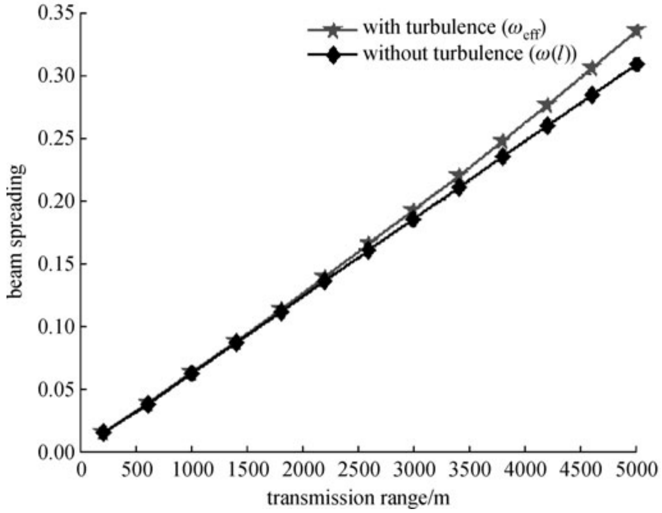

Fig. 2 Beam spreading versus transmission range

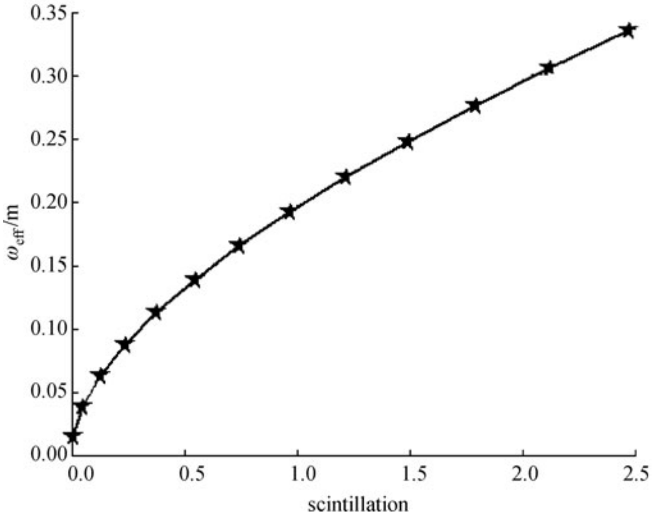

Fig. 3 Waist of beam with turbulence versus scintillation

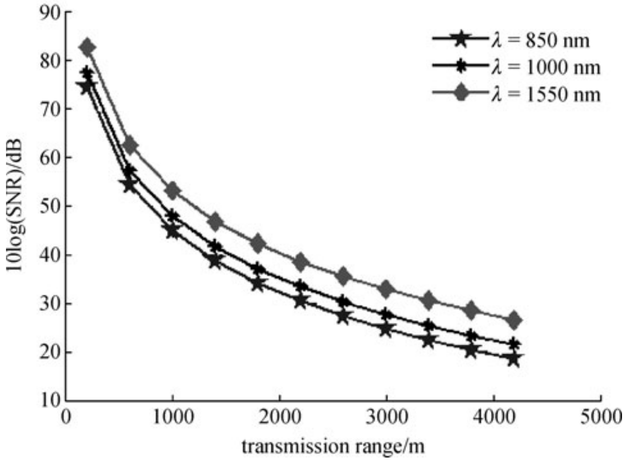

Fig. 4 SNR versus transmission range

and receiver increases, the SNR decreases. This means that the increment of link range is able to decrease the transmission quality and efficiency of FSO systems. At a low range of 200 m, the SNR is about 74 dB for 850 nm, 77 dB for 1000 nm, and 82 dB for 1550 nm. For 4000 m, the SNR is about 18 dB for 850 nm, 21 dB for 1000 nm, and 26 dB for 1550 nm.

Figure 5 shows the BER versus the transmission range. As the link range between transmission and receiver increases, the BER increases too. At 2500 m link range, the BER is about 10^{-4} for 850 nm, 10^{-6} for 1000 nm, and 10^{-9} for 1550 nm. At 4000 m, the BER is 10^{-2} for 850 nm, 10^{-3} for 1000 nm, and 10^{-4} for 1550 nm. If we want an acceptable communication BER of 10^{-9}, the maximum link range between transmitter and receiver should be about 1600 m for 850 nm, 1900 m for 1000 nm, and 2500 m for 1550 nm.

Figure 6 indicates SNR versus expansion of the beam size resulting from air turbulence. For a beam size of $\omega_{\mathrm{eff}}(l)$ = 0.015 m, the SNR = 64 dB and $\mathrm{SNR}_{\mathrm{eff}}$ = 62 dB, but for $\omega_{\mathrm{eff}}(l)$ = 0.33 m, the SNR = 4.7 dB and $\mathrm{SNR}_{\mathrm{eff}}$ = 3.4 dB. From these results, we conclude that when the beam expands, the loss in terms of the beam intensity increases. This leads to the decrease in the SNR value, and therefore the BER increases as indicated in Fig. 7. For a spot size of 0.015 m, the BER = 10^{-115}, and when the spot size of the beam is 0.33 m, the BER increases up to 10^{-5} approximately. From the results above, we conclude that the narrow beam shows a limited effect of the atmospheric turbulence on the intensity.

Figure 8 shows the BER versus link range between transmitter and receiver. Figure 8 graphically represents the BER as a function of the irradiance variance. For 3500 m, BER is 10^{-6} for the SNR and 10^{-5} for the $\mathrm{SNR}_{\mathrm{eff}}$. For an irradiance variance 0.05 the BER 10^{-6} for the SNR and 10^{-5} for the $\mathrm{SNR}_{\mathrm{eff}}$. From the results obtained, we conclude that to improve the performance of the FSO transmission systems, it is recommended to shorten the link range between transmitter and receiver. Another improvement of the signal quality offered by the FSO systems includes using the 1550 nm wavelength. The SNR of FSO systems with 1550 nm wavelength is higher than that corresponding to 1000 and 850 nm wavelengths. To reduce the atmospheric turbulence effects on FSO systems, we suggest using the 1550 nm wavelength. Moreover, for the 1550 nm wavelength, the allowable power is largely higher compared to smaller wavelengths (about 50 times compared to 850 nm). This shows that the system operates well during heavier attenuation of the atmosphere since we can safely increase power at the source.

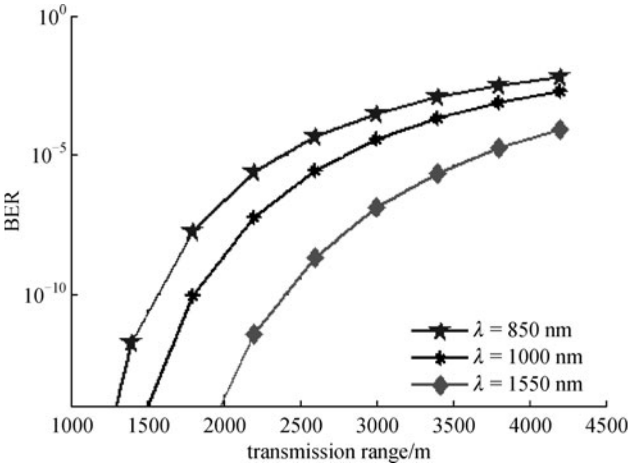

Fig. 5 BER versus transmission range

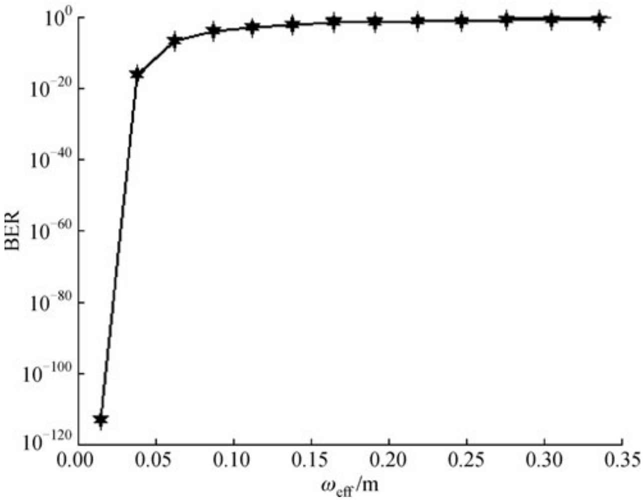

Fig. 7 BER versus waist of beam with turbulence

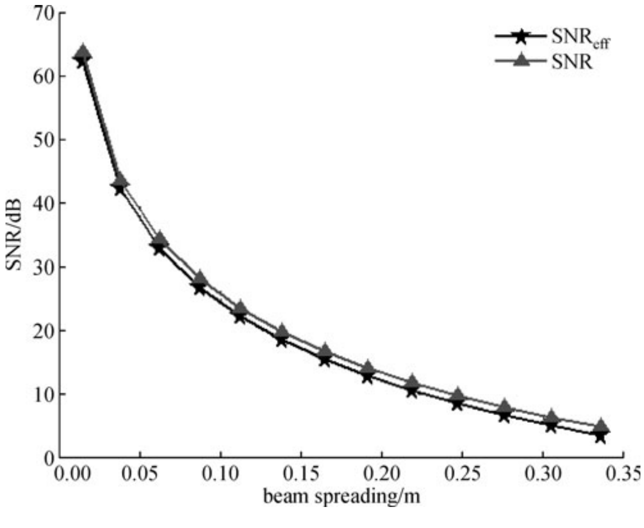

Fig. 6 SNR with and without turbulence, $\mathrm{SNR}_{\mathrm{eff}}$ and SNR, respectively, versus transmission range

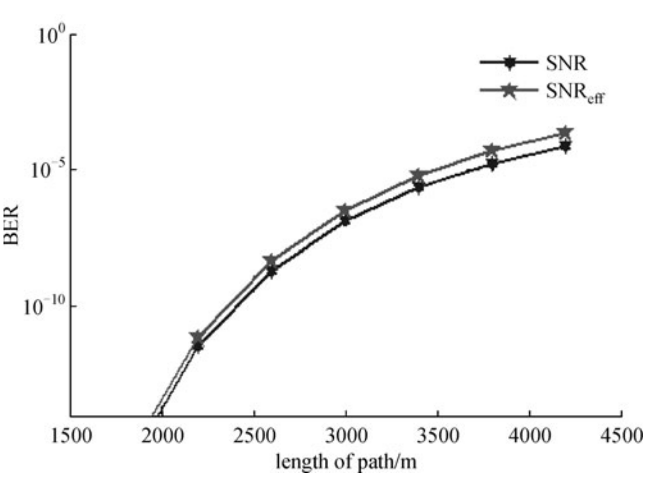

Fig. 8 BER versus transmission range for SNR and $\mathrm{SNR}_{\mathrm{eff}}$

5 Conclusion

In this paper, we focused on the scintillation effects on the performance of FSO links. The analysis was carried out for the variance, SNR, and BER in the environment of Yemen. Scintillation for the Yemen environment is wavelength and distance dependent. The wavelength of 1550 nm turned out to be interesting since it is less sensitive to atmospheric turbulence and harmless to the human eye. The results indicate that the performance of the FSO system is good during the worst conditions in Yemen. To improve the transmission efficiency of FSO systems, the wavelength of 1550 nm must be used and the distance between transmitter and receiver must be reduced. To achieve a BER of 10^{-9} during air turbulence, the distance between transmitter and receiver should be 2600 m. Thus, the FSO system may be applied in Yemen efficiently even in case of the presence of air turbulence.

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