Performance of Free Space Optical Communication Link Under Foggy Weather Regarding Different Wavelengths

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Abstract: The stochastic influence of weather conditions on atmospheric channel limits the availability and stability of the free space optical (FSO) system. Foggy weather is the main challenge of free space optical communication system. Based on the attenuation model of laser in foggy weather, this paper simulates and analyses the influence of fog on transmission performance objectives such as bit error rate and quality factor of FSO system with different operating wavelengths. The simulation results show that the scattering effect of fog particles is related to the transmission wavelength, the lower the operating wavelength, the greater the fog attenuation, and the wavelength window of 1550nm is more suitable to FSO system.

1 INTRODUCTION

Free Space Optics (FSO) is a communication method in which the laser beam uses the atmosphere as the transmission medium to establish a connection between the transmitter and receiver and transmits high bandwidth data. FSO combines many features of wireless communication and optical communication, and can realize large capacity broadband data transmission, which has the characteristics of flexibility in networking, no spectrum authorization, outstanding anti-electromagnetic interference ability and good confidentiality. However, free space optical communication is vulnerable to atmospheric turbulence and path loss such as rain, fog and cloud, and its availability needs to be further improved.

The main factors affecting free space optical communication link are absorption, scintillation and scattering. An obvious defect of FSO link in troposphere is its sensitivity to weather conditions. Various weather conditions such as rain, fog, snow and haze, will have varying degrees of impact on optical transmission (Nebuloni, 2005). Small changes in atmospheric transmission path may lead to changes and distortions in laser beam. Some unpredictable environmental factors may even produce very strong attenuation in the optical links, which will eventually affect the transmission performance of FSO systems, and even the communication failure and interruption will be caused. It can be said that the performance of FSO system is highly dependent on the weather conditions at the deployment site. Therefore, the weather of the deployment site should be investigated in advance before the actual deployment of FSO system.

The stochastic influence of weather conditions on atmospheric channel limits the availability and stability of FSO system, which leads to the fact that this system has not been widely used. This paper focuses on the influence of foggy weather on FSO system. Fog is considered to be the main challenge of FSO system (Madhuri et. al., 2018). Under the conditions of dense marine fog and medium continental fog, optical signal attenuation can even reach 480dB/km (Khan and Muhammad, 2012) and 130dB/km (Flecker et. al., 2006). Fog particles are spherical in shape and have radii varying between 0.01 and 15μm, depending on geographical location (Muhammad and Sheikh, 2007). Mie scattering is dominant in foggy weather, which resulting in optical attenuation. The beam in free space is most easily attenuated by fog drops, which makes fog become a key factor in the attenuation of optical power and irradiance. Flecker et. al. made a detailed analysis of the experimental test results of the continental city Graz and the coastal city Nice, and compared the different characteristics of the marine fog and the

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continental fog in optical attenuation (Flecker et. al., 2006).

According to the different application scenarios, the FSO system adopts various wavelengths for communication transmission. The selection of its operating wavelength is mainly based on the attenuation of optical signals in the atmosphere. Although lasers at 1060nm have very low attenuation values in atmospheric transmission, few FSO systems currently operate at this wavelength due to the difficulty of finding optical transmission devices working at this wavelength. Optical receiving and transmitting components with operating wavelength of 850nm have low manufacturing cost and small attenuation. Some low-cost FSO systems mainly work in this wavelength window (Dautov et. al., 2017). The wavelength window of 1550nm also has a wider range of low loss window, which is convenient for the transmission of WDM signals. Therefore, this wavelength window has become another major option of FSO system. Gebhart et. al. provide comparisons of fog attenuation effect of different wavelengths, however the influence of fog attenuation effect on the transmission performance of FSO system has yet to be further investigated (Gebhart et. al., 2005). Madhuri et. al. analysed the optical power and quality factor of FSO system operating at 1310nm, but lacked the comparative analysis of the system operating at 850nm and 1510nm (Madhuri et. al., 2020).

In order to improve the design of free space optical communication systems, this paper primarily concentrates on the internal parameters which are transmission wavelength, bit rate, quality factor, link range for the performance analysis of the terrestrial FSO link under fog weather conditions. Two different wavelengths (850nm, 1550nm) are used in order to find the most appropriate operating wavelength for transmission of signals. OptiSystem software is used to simulate all the above parameters. The organization of this paper is as follows: The effect of foggy weather condition on FSO system and the models of fog attenuation are discussed in Section 2. Following that, the simulation experimental system of the free space optical communication is set up in Section 3. The results are presented and discussed in the next section.

2 ATTENUATION MODEL

The attenuation of fog can be calculated both theoretically and empirically. The theoretical research comes from the Mie scattering theory. Because the shape, direction and complex chemical composition of fog particles cannot be predicted prior, it is very complicated and time-consuming to calculate the attenuation coefficient by means of the Mie scattering theory. To overcome this, an empirical model is usually used to predict the attenuation effect of fog on laser propagation based on actually measured visibility value (Anandkumar and Sangeetha, 2021).

The earliest empirical model used by the researchers to calculate fog attenuation is the Kruse model, which is convenient in the narrow wavelength range of 785-1550 nm. The attenuation coefficient is expressed as

$$\beta(\lambda) = \frac{3.912}{V}\left(\frac{550}{\lambda}\right)^q \tag{1}$$

where, $\beta(\lambda)$ represents the atmospheric attenuation coefficient, V is the measured visibility value (km), λ represents the optical wavelength (nm), and q represents the size distribution parameter of scattered particles, and its common values can be obtained according to the Kruse model (Alkholidi and Altowij, 2014).

$$q = \begin{cases} 1.6, & V \geq 50km \\ 1.3, & 6km \leq V < 50km \\ 0.585V^{1/3}, & V \leq 6km \end{cases} \tag{2}$$

The formula for calculating fog attenuation coefficient using the Kruse model is related to visibility, which is more convenient and practical in the narrow wavelength range of 785-1550 nm. However, in the strong fog or haze weather with visibility less than 6km, there is a certain deviation in the Kruse model, and the Kim model (Kim et. al., 2001) modifies the q value in the Kruse model.

$$q = \begin{cases} 1.6, & V \geq 50km \\ 1.3, & 6km \leq V < 50km \\ 0.16\,V + 0.34, & 1km \leq V < 6km \\ V - 0.5, & 500m \leq V < 1km \\ 0, & V < 500m \end{cases} \tag{3}$$

The Kim model is an extension of the Kruse model, which helps to obtain better accuracy in low visibility. In order to better predict the attenuation effects of different types of fog, Bouchet et. al. proposed the Advection model and the Radiation model respectively for advection fog and radiation fog in the atmospheric (Bouchet et. al., 2005).

$$\gamma_{adv\_fog}(\lambda) = \frac{0.11478\lambda + 3.8367}{V} \tag{4}$$

$$\gamma_{rad\_fog}(\lambda) = \frac{0.18126\lambda^2+0.13709\lambda+3.7205}{V} \quad (5)$$

At this point, the calculation expression of fog attenuation coefficient is

$$\beta(\lambda) = \frac{10}{\ln(10)} \cdot \gamma(\lambda) \quad (6)$$

In advection fog, the atmospheric particles move laterally or horizontally, while in radiation fog, they move circumferentially. Based on the particle distribution and density of atmospheric channel, the Bouchet model is suitable for advection fog and radiation fog with wave length of 690-1550nm and visibility of 0.05-1km, which not only reflects the visibility factor, but also describes the relationship between optical attenuation and wavelength in different types of fog.

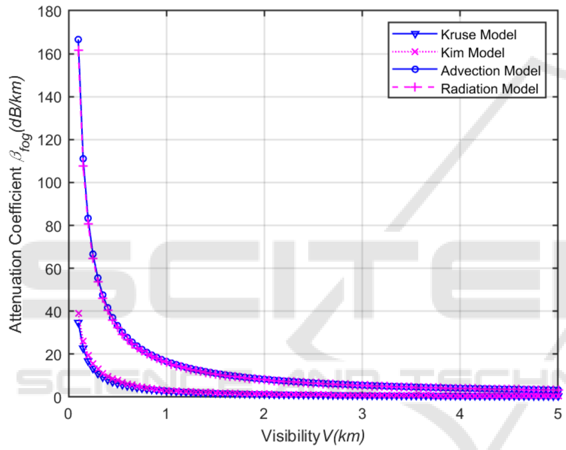


Figure 1: Relationship between fog attenuation coefficient and visibility with different models.

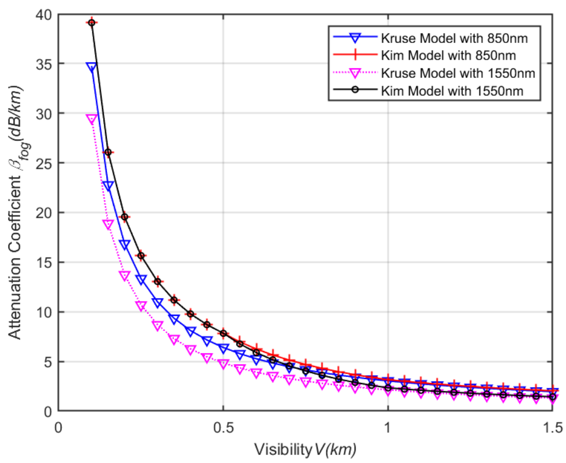


Figure 2: Relationship between fog attenuation coefficient and visibility with different wavelengths.

Kim, Kruse and Bouchet (advection fog and convective fog) models are the most commonly used empirical models to predict fog attenuation coefficient using visibility. Figure 1 depicts the variations of the fog attenuation coefficient with different visibility which is calculated by using different empirical models. It can be seen that the attenuation coefficient is closely related to visibility. With the decrease of visibility, the attenuation coefficient gradually increases. This trend is more significant when the visibility is less than 100m (i.e. in dense foggy weather), and the attenuation coefficient can even reach more than 100dB/km at this time. Figure 2 further describes the influence of different wavelengths (850nm and 1550nm) on the fog attenuation coefficient. As the transmission wavelength increases, the attenuation coefficient decreases, which is more obvious in the Kruse model.

Table 1 shows the attenuation coefficients of laser in different levels of fog calculated by the Kruse model and the Kim model, it can be seen that in the cast of mist, compared with the wavelength of 850nm, the optical signal operating at 1550nm suffers less attenuation.

Table 1. Attenuation coefficient in foggy weather.

Fog level	Visibility (km)	The attenuation coefficient (dB/km)			
		The Kruse Model		The Kim Model	
		850nm	1550nm	850nm	1550nm
Mist	10	0.22	0.10	0.22	0.10
	4	0.65	0.37	0.64	0.35
	2	1.42	0.91	1.47	0.99
	1	3.03	2.13	3.15	2.33
Heavy fog	0.5	6.39	4.84	7.82	7.82
	0.2	16.85	13.72	19.56	19.56
Dense fog	0.05	71.23	62.58	78.24	78.24

3 SIMULATION EXPERIMENT SYSTEM

OptiSystem software is used to simulate the wireless optical communication system. The simulation experiment system uses the OOK modulation scheme is the simplest scheme and is widely applied in the commercially available FSO systems. OOK is very sensitive to channel turbulence. Non-Return-to-Zero (NRZ) and Return-to-Zero (RZ) OOK models are often used within the OOK modulation scheme due to their easy implementation and cost effectiveness. The NRZ OOK modulation provides higher bandwidth

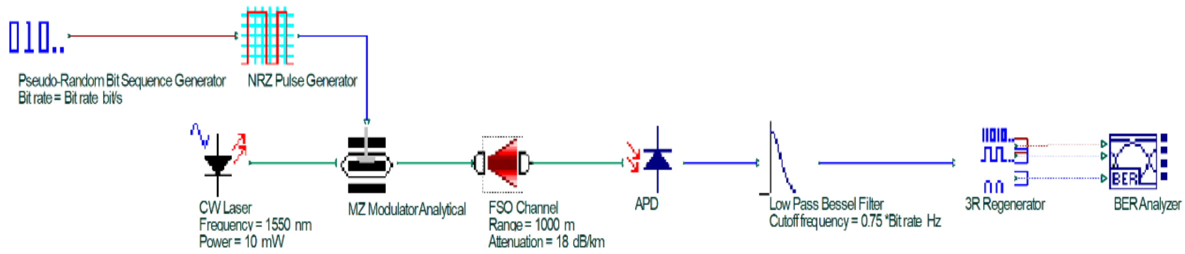


Figure 3: FSO system designed in OptiSystem.

efficiency than the RZ OOK. In order to analyse the influence of foggy weather on FSO transmission performance, the simulation experimental system of the free space optical communication is set up as shown in Figure 3.

In the simulation system, the CW Laser is used to generate carrier optical signal. Two lasers with different wavelengths (850nm and 1550nm) were used to compare the influences of wavelengths on the transmission performance of the link. The Pseudo-Random Bit Sequence Generator generates a sequence of input data bits at a rate of 155.520Mbps. Then, a Non-Return-to-Zero Pulse Generator (NRZ Pulse Generator) is used to code modulate the input data as the modulation input of the external modulator. Then the carrier signal is encoded by a multiplexer, and the non-return to zero code signal generated by the Non-Return-to-Zero Pulse Generator is loaded into the optical carrier signal via On-Off Keying modulation (OOK) in the external Mach-Zehnder Modulator. Finally, the optical signal generated by the modulation is transmitted to the receiver through the free space optical channel (FSO Channel).

The receiving part of the simulation system is composed of photoelectric detector, low pass filter, error analyzer. In the experiment, the receiver detector adopts APD photoelectric detector, which can improve the sensitivity of the receiving system. Low Pass Bessel Filter is used to filter the noise. The BER analyzer and 3R Regenerator are used to test the system transmission performance. The specific parameters of the simulation experiment system are shown in Table 2.

Table 2. Parameters of FSO system

Parameters	Value
Transmitter aperture diameter, d_t (m)	0.05
Receiver aperture diameter, d_r (m)	0.15
Beam divergence, θ (mrad)	1
Transmitted optical power, $P_{transmit}$ (dBm)	10
Wavelength, λ (nm)	850,1550
Link Range, L (km)	0.6~3

4 RESULTS AND DISCUSSIONS

Figure 4 and Figure 5 show the variation of system transmission performance with link range under foggy weather in different visibility. Figure 4 is the result of Quality factor (Q-factor), and Figure 5 is the result of average bit error rate. The greater the visibility, the less the fog effect, and according, the average bit error rate of the system is lower, the Q-factor value is higher, which means the transmission performance is good. When the visibility is 10km and the link range is 2.7km, the requirement of average bit error rate (BER $\leq 10^{-9}$, corresponding Q-factor $\geq$ 6) can still be met. When the visibility is 1km, the system performance degrades due to the large attenuation. When the operating wavelength is 1550nm, the maximum available link length of the system is 2.6km. When the operating wavelength is 850nm, the maximum available link length of the system is only 2.35km. If the link range exceeds the maximum available length, the transmission quality cannot be guaranteed, and the link transmission may even be blocked.

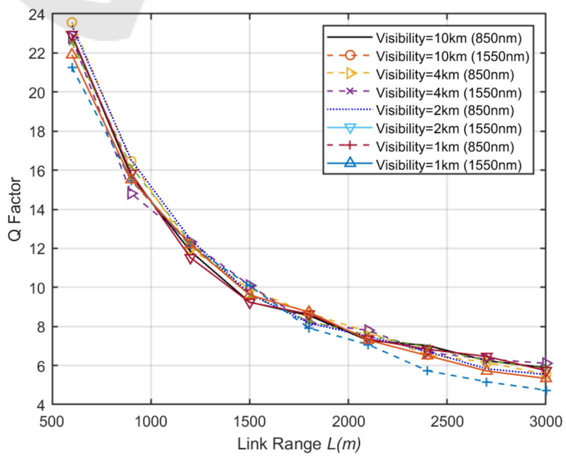


Figure 4: Influence of different fog weather on Quality factor (Q-factor).

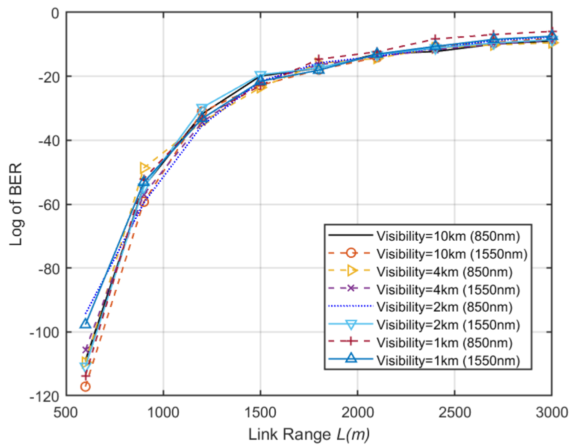
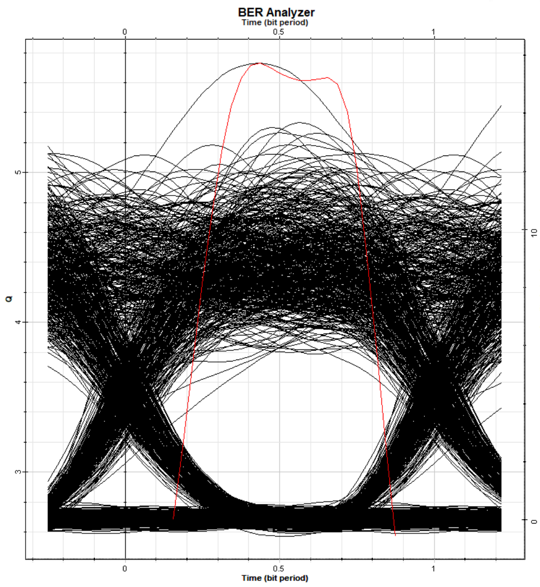
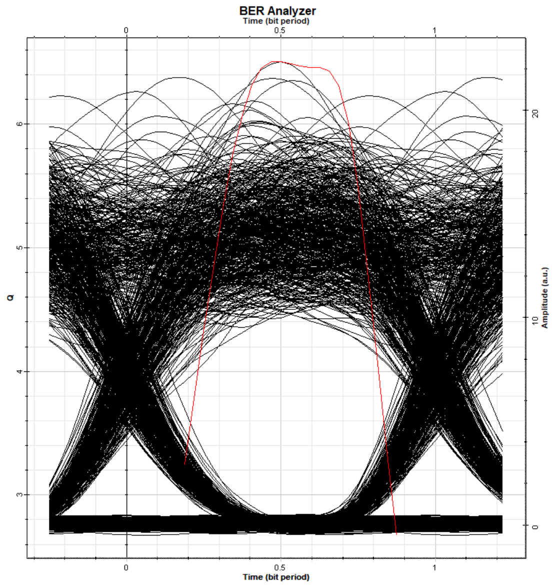


Figure 5: Influence of different fog weather on average BER.

Figure 6 shows the eye diagrams of two systems with different operating wavelengths when the visibility is 1km and link range is 2.1km. Figure 6 (a) is a system with an operating wavelength of 850nm. At this time, the opening eye pattern is small, the eye height which indicating the opening size of eye is 4.20×10^{-6}, the bit error rate is 3.33×10^{-9}, and the Q-factor is 5.73, which is not enough to ensure the transmission quality of the system. Figure 6 (b) shows the system with an operating wavelength of 1550nm, and the opening eye pattern is better. The eye height is 7.64×10^{-6}, the corresponding bit error rate is 2.39×10^{-11}, and the Q-factor is 6.50. The transmission performance of the system is stable, and the transmission distance of the system can be further increased.



(a)



(b)

Figure 6: Eye diagram of two systems with different operating wavelengths in foggy weather (a) 850nm and (b) 1550nm.

It can be seen from the simulation experiment that the system with the operating wavelength of 1550nm has a higher Q-factor and better transmission performance. At the same time, the system with 1550nm operating wavelength can still meet the requirements of system bit error rate ($\leq 10^{-9}$) at 2.6km, while the system with 850nm operating wavelength can no longer satisfy the requirements of system transmission quality at 2.35km, and the maximum transmission distance of the system is relatively short.

5 CONCLUSIONS

As the size of fog particles is equivalent to the operating wavelength of FSO system, foggy weather has the most prominent influence on the atmospheric transmission link among various weather phenomena. The scattering effect of fog particles in the atmosphere will lead to the attenuation of the transmission beam, weaken the received optical power, affect the transmission performance of the system, and even cause the interruption of the system. The scattering effect of fog particles is related to the transmission wavelength. The larger the operating wavelength is, the smaller the attenuation is. In this case, the transmission quality of FSO system is better, and the transmission link range is also longer.

Therefore, by predicting the effects of foggy weather on FSO systems with different operating wavelengths in advance, the resulting performance degradation can be estimated and the outage probability can be reduced.

The simulation experiment system uses the OOK modulation scheme is the simplest scheme and is widely applied in the commercially available FSO systems. OOK is very sensitive to channel turbulence. This paper studies the performance of Free Space Optics communication method in foggy weather taking in consideration different wavelengths while implementing the simulation. A new practical means to further facilitate wireless communications is provided, and these results can be at a point of reference, in designing a Future FSO system.

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