Performance analysis of terrestrial 6G networks in tropical region

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Article Info

Article history:

Received Feb 5, 2024
Revised Jul 14, 2024
Accepted Aug 5, 2024

Keywords:

Availability
Free space optical
Haze attenuation
Sixth generation networks
Visibility

ABSTRACT

Next-generation (NG) optical technologies are expected to offer high data rates, multiple broadband services, expandable bandwidth, and flexible communication options for diverse end users. In optical technologies, free space optical (FSO) technology stands out as a promising component to meet the requirements of terrestrial sixth generation (6G) networks. This is due to its cost-effectiveness, ease of deployment, high bandwidth capacity, and robust security features. However, haze and rain are major challenges to FSO link performance. These adverse weather conditions reduce visibility, causing significant attenuation of the laser signal. The resulting attenuation negatively impacts the performance and availability of the FSO link. This paper assesses the performance of a terrestrial FSO link under tropical climate conditions. Predicted attenuation due to haze is analyzed and compared using two wavelengths: 850 nm and 1550 nm. The predicted attenuation is based on a whole year of visibility data in Malaysia, from January 1, 2023 to December 31, 2023. Additionally, the availability of the two wavelengths is evaluated. The findings show that higher wavelengths experience lower attenuation compared to lower wavelengths. These results provide valuable insights into the feasibility of deploying FSO links in tropical climates.

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1. INTRODUCTION

Free space optical (FSO) is a wireless communication system that uses the optical spectrum. Initially designed for satellite and military applications in remote areas, FSO has evolved to become a prominent technology for last-mile and point-to-point communication [1]-[4]. The huge data transmission needs of the future can be fully accommodated by line-of-sight (LOS) optical wireless transmission links, FSO links can offer the highest data rates for communication because of its high carrier frequency, which is in the range of 20 to 375 THz [5]-[8]. Avoidance of electromagnetic pollution, ease of installation, license-free communication, and security against wiretapping are an examples of FSO system advantages [9]-[12].

The transmission of optical signals is negatively affected by the atmospheric channel, leading to a degradation in system performance [13]-[15]. A variety of gases including dust and aerosols are suspended in the earth's atmosphere. The optical signal undergoes interactions with these particles resulting in attenuation. Therefore, we can state that FSO communication is highly dependent on the climatic factors and the geographical location of the FSO link [16]. The FSO signal in propagation experiences scattering and absorption when it interacts with these tiny atmospheric particles, causing a degradation in the quality of the transmitted signal [17]-[19]. In addition to terrestrial sixth generation (6G) networks for back-hauling connectivity [20], FSO systems are often utilized as the local area networks (LAN) link between buildings or as the last-mile communications connection. Figure 1 illustrates some of the FSO communication system applications for terrestrial networks to establish LOS connection between two transceivers over atmospheric channel. Link availability for carrier-class applications in telecommunications is usually expected to be 99.999%. In comparison, 99% link availability is usually sufficient for enterprise-class LAN applications [21].

Figure 1. Deployment of FSO links

Using local meteorological data is crucial for an accurate prediction of FSO link availability. One important factor to consider when predicting atmospheric attenuation due to haze is visibility which is related to particle size distribution [22]. FSO availability in tropical weather conditions can be realistically assessed by using measured visibility data in tropical climate such as Malaysia. Based on our study of the collected data, Malaysia has an average visibility of 9 km. This study computes availability using the FSO system's link budget and measured visibility data. To predict atmospheric attenuation due to haze, empirical models are used based on measured visibility data. We inspect how haze attenuation affects FSO link availability by examining the ranges of two typical laser beam wavelengths employed in FSO systems that are commonly utilized in business applications. The maximum operational range for FSO systems under various availability conditions is suggested in this paper. Additionally, it provides suggestions to telecommunication services providers regarding achievable availability indicators that may be considered for setting in FSO links as a last-mile option.

2. HAZE-INDUCED ATTENUATION

Different suspended particles are encountered by the FSO signal as it propagates through the atmosphere including aerosol particles and gases molecules. Degradation results from these particles' interactions with the optical signal. The main causes of the FSO signal's attenuation are scattering and absorption in the atmospheric channel. The absorption is dependent on the wavelength that is utilized to transmit data, and it is generally very small and insignificant in the operating wavelength range of FSO links. Scattering is wavelength-dependent (λ) and It is divided into three categories according to the size of air particles (r): i) non-selective scattering ($r \gg \lambda$); ii) Mie scattering ($r \approx \lambda$); and iii) Rayleigh scattering ($r \ll \lambda$). The absorption and scattering of infrared light by atmospheric gas molecules and aerosols produces atmospheric attenuation. Using the exponential Beer-Lambert law, atmospheric attenuation can be calculated as (1) [23]:

$$\sigma = e^{-\beta l} \tag{1}$$

where l is the distance at which measurement occurred and β is the specific attenuation coefficient per unit of length. Mie scattering is preferred over Rayleigh and nonselective scattering because of the same sizes of haze and fog particles suspended in the atmosphere and the wavelength of the optical signal and it is given as (2) [24]:

$$\beta = \frac{3.912}{V}\left(\frac{\lambda}{550nm}\right)^{-q} \tag{2}$$

where V is the visibility (km) and λ is wavelength (nm) and q is the size distribution of the scattering particles. The value of q is derived experimentally for high, moderate, and low visibility and given as (3).

$$q = \begin{cases} 1.6\ for\ V > 50km \\ 1.3\ for\ 6 < V < 50km \\ 0.16V + 0.34\ for\ 1 < V < 6km \\ V - 0.5\ for\ 0.5 < V < 1km \\ 0\ for\ V < 0.5km \end{cases} \quad (3)$$

3. FREE SPACE OPTICAL LINK MARGIN

A link power budget analysis is a crucial task for an efficient communication system designer to create a reliable communication system. This analysis considers all recognized power loss sources in the transmitted power. Haze-induced attenuation is considered in this investigation's link budgeting procedure. The link margin is the difference between the power received and the sensitivity of the receiver. The requirement for link availability signifies that the link will operate only if the link margin does not exceed a defined receiver sensitivity. Increasing atmospheric attenuation due to reduced visibility leads to a reduction in optical received power. This decrease in received optical power falling below the receiver sensitivity threshold could result in an FSO link outage. The link margin is defined as (4):

$$LM\ (dB) = P_t + |S_r| - cl - Att_{Geo} - Att_{Haze} \quad (4)$$

where P_t is the transmitted power in dBm, $|S_r|$ is the absolute value of the receiver sensitivity in dBm, cl is the coupling losses, Att_{Geo} is the geometric loss in dBm, and Att_{Haze} is the haze-induced attenuation in dB. The geometric loss in dB given as (5) [25]:

$$Att_{Geo} = 20log\left(\frac{L\theta}{D}\right) \quad (5)$$

where L is the FSO link distance (km), θ is the divergence angle (mrad), D is the aperture diameter of receiver lens (cm).

4. MEASURED VISIBILITY

The distance at which the contrast of an object's image drops to 2% of its initial value is known as visibility. The wavelength at which the human eye is most sensitive, 550 nm is used for this measurement, technically, visibility or visual range is the distance at which light diminishes to 2% of its transmitted power, measured visibility data of year 2023 was obtained from National Oceanic Atmospheric Administration (NOAA) [26], NOAA agency plays a vital role in providing accurate weather forecasts, monitoring oceanic, and atmospheric conditions. It was decided that a forward scatter meter would work perfectly as a visibility sensor. The most successful method was to use a visible light source along with the forward scatter meter, since this better matched observer judgments for small particle occurrences such as haze. The visibility data was captured in the meteorological station at Kuala Lumpur airport from January 1, 2023 to December 31, 2023, the station is located (lat: 2.745578, long: 101.709917), the data recorded on hourly observation and based on one year data, a visibility sensor designed to capture data during rapid changes is likely intended to monitor and record information specifically when there are sudden fluctuations or significant variations in visibility conditions. The average visibility is 9 km in KL airport. The equipment specifications for the visibility measurements are shown in Table 1.

Table 1. Visibility sensor specifications

Item	Specification
Range	10 m to 75 km
Accuracy	+ 2%
Light source	880 nm/infrared
Weight (sensor head)	7 kg
Forward scatter meter angle	45°
Operating temperature range (°C)	- 50 to +60

5. RESULTS AND DISCUSSION

Captured visibility data for the year 2023 been processed in order to establish the cumulative distribution function (CDF) as shown in Figure 2. The percentage of time exceeding 1% corresponds to approximately 4 km of visibility as shown in Figure 2, the highest value of visibility is 12 km but 0.5 kilometers is the lowest visibility value. The haze-induced atmospheric attenuation was predicted by using (1). Calculating the CDF of visibility data is a powerful tool for understanding the statistical characteristics of visibility in the atmosphere with the use of the equal probability correlation approach between the haze attenuation and the CDF of measured visibility.

Atmospheric attenuation varies based on wavelength as shown in Figure 3 for 100% exceeded time which corresponding to maximum measured visibility 12 km; the atmospheric attenuation is 0.8 km/dB and 0.4 dB/km for anticipated wavelength 850 nm and 1550 nm respectively whereas the attenuation increases to 14 dB/km and 10 dB/km utilize 850 nm and 1550 nm wavelengths respectively at 0.1% of exceeded time which corresponds to 1 km visibility. This attenuation indicates that using higher wavelength will improve the performance of FSO link compared to lower wavelength. Also, for worst weather condition (visibility is ≤500 m); the attenuation appears to be wavelength independent.

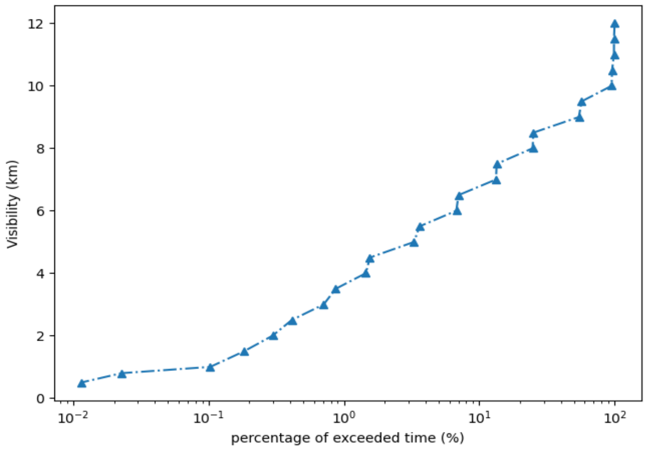

Figure 2. Cumulative distribution of the visibility data measured in Malaysia during year of 2023

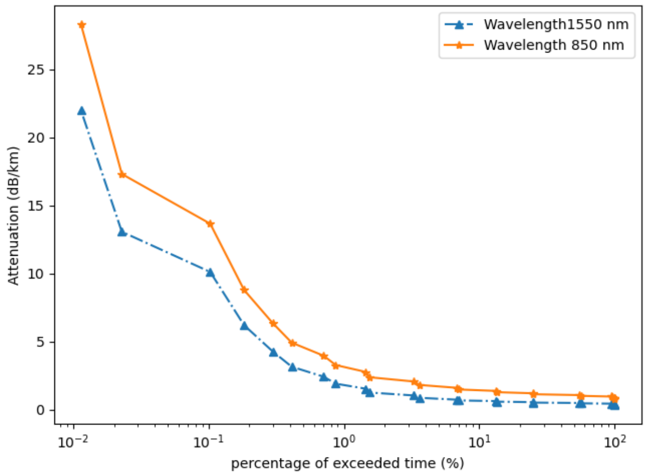

Figure 3. CDF of predicted atmospheric attenuation based on visibility data measured in Malaysia

To evaluate the haze impact on FSO link range up to 5 km; using two wavelengths 850 nm and 1550 nm, haze-induced atmosphere attenuation has been calculated for the FSO link range from 2 km to 5 km as shown in Figure 4. To achieve 99.8% availability, which corresponds to 0.2% downtime for a 5 km FSO link distance; 15 dB and 32 dB power margin are needed for FSO link utilizing 1550 nm and 850 nm wavelength respectively. Almost twice as much power margin is required for the 850 nm wavelength as there is for the 1550 nm wavelength for the same availability. FSO system factors in Table 2 are considered for link budget calculations, coupling losses is considered as 4 dBm and geometric loss is predicted using (5). Link margin is analyzed over variation with FSO link range and different wavelengths as shown in Figure 5. FSO link availability pattern determined by link margin and corresponding haze-induced attenuation and shown in

Figure 6 for 99.9% FSO link availability; the link's range can be deployed over 1.5 km using an 850 nm wavelength, while the link's range can be deployed 2.5 km when employing a 1550 nm wavelength.

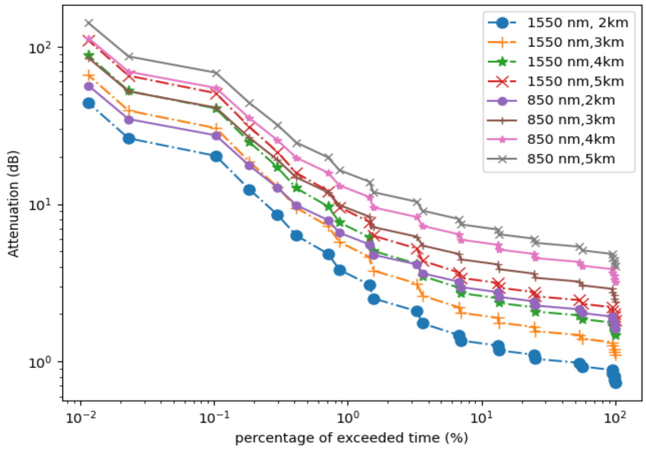

Figure 4. Atmospheric attenuation for two wavelengths up to 5 km link distance

Table 2. FSO system parameters

Item	Specification
Transmitted power (Pt)	13 dBm
Beam divergence (θ)	2 mrad
Aperture diameter of receiver lens (D)	0.08 m
System coupling losses (cl)	4 dBm
Receiver sensitivity (Sr)	-39 dBm

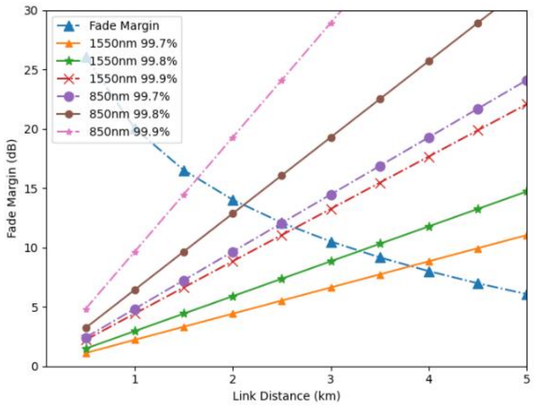

Figure 5. System fade margin under effect of haze

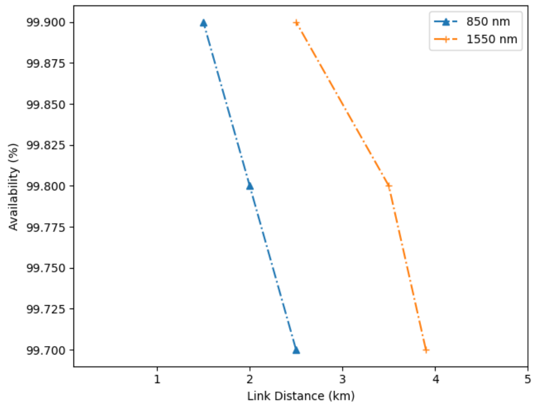

Figure 6. FSO link availability for two wavelengths under haze effect

6. CONCLUSION

The overall performance and availability of a FSO link are impacted by internal factors within the FSO system, including parameters such as wavelength, beam divergence, receiver lens diameter and receiver sensitivity. Additionally, the link's availability is impacted by local climate. In this paper, FSO system performance has been investigated and analyzed by using captured visibility data in Malaysia, two different wavelengths were utilized 850 nm and 1550 nm. The highest wavelength has less impact of haze attenuation. Low visibility increases the attenuation and decreases the link performance and its availability. To achieve a link availability of 99.9%, the optimal deployment range is 2.5 km for the 1550 nm wavelength and 1.5 km for the 850 nm wavelength. Haze attenuation remains consistent across wavelengths when visibility is below 500 m. Enhancing the availability of FSO links is advised through effective strategies, including the implementation of hybrid FSO and backup radio frequency systems.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the funding support provided by the Higher Institution Centre of Excellence (HICOE), Ministry of Higher Education Malaysia through the Wireless Communication Centre (WCC) Vot. No. R.J130000.7823.4J642.

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