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Research Paper

Visibility effect on the availability of a terrestrial free space optics link under a tropical climate

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ABSTRACT

Haze, fog and rain limit the visibilities and acts as dominant parameter for free space optics availability estimation. Low visibilities increase atmospheric attenuation and reduce the availability of optical signals from free space optics (FSO) links. Thus, this study determines the effect of visibility on FSO link availability in a tropical climate. Visibility data were measured in Malaysia for three years and used to estimate availability of FSO links. Rain and haze are two phenomena which reduces the visibility in tropical climate like Malaysia. Hence three cases were considered for measured data analysis: rain with dense haze, dense haze, and normal haze cases. In Malaysia, seasonal dense haze is mainly attributed to forest fires in Indonesia and in parts of Malaysia. The atmospheric attenuations predicted based on measured visibility (km) were compared across the three cases. The attenuations in the first two cases are found severe (almost 155 dB/km); while in the third case it is very low (almost 6 dB/km). The worst case (dense haze) is equivalent to a thick fog in temperate regions and must be examined carefully with respect to FSO deployment in a tropical environment.

1. Introduction

Free space optics (FSO) is an outdoor optical wireless technology that uses optics to transmit data at a speed of up to 2.5 Gbps (Su et al., 2012). This technology is characterized by line of sight and high security. Atmospheric weather is the sole challenge to this technology (Willebrand and Ghuman, 2002); particles suspended in the air interact with the photons of the optical signal, thus inducing the absorption or scattering of this signal (Weichel, 1990). Scattering occurs when the particle is significantly smaller than the optical wavelength (McCartney, 1976). By contrast, a large particle causes optical signal absorption. Visibility (km) is the most important weather parameter for estimating atmospheric attenuation due to fog and haze (Achour, 2002). In temperate regions, snow is a factor that can reduce the availability of FSO links as well. Dominant attenuation occurs when hydrometeors such as rain and snow are combined (Wilfert et al., 2010). Another study that was conducted in a temperate region examined only attenuation as a result of scattering via visibility data and turbulence caused by scintillation (Prokes, 2009). In tropical regions without fog, heavy rain attenuation can be estimated and is expected to be a main cause of FSO link unavailability (Suriza et al., 2013). The average visibility in Malaysia is 10 km, which is considered good weather. Haze consists of smoke, dust, and other dry air particles that impair visibility. Fog is composed of small water drops suspended in the atmosphere (Achour, 2002). A thick fog has a visibility that varies between 50 and 250 m under a certain weather condition (Kim et al., 2001). As per our analysis of collected data, visibility ranges between 0.1 and 0.5 km in the event of forest fires in Indonesia and in parts of Malaysia. The visibility in such a case exhibits almost the same distance variation as that during a thick fog. Both weather phenomena impair visibility and reduce the availability of optical signals. Therefore, these cases must be examined carefully in relation to FSO system deployment (Kim and Korevaar, 2001). To determine whether or not visibility is also reduced by rain in a tropical region, the three years visibility data categorized into three sets and consider three scenarios. The first scenario covers all weather conditions; all weather data, including rain, dense haze, and normal haze, are taken into account. Three years' worth of data are obtained from an entire sample space. The second scenario is that under dense haze, in which rain data are discarded. These two scenarios are considered the worst-case scenarios. Finally, the third scenario is that under normal haze, which excluded rain data and the data collected during a period wherein forest fires occurred in neighboring countries which is the visibility data measured in August 2005 and in October and early November of 2006.

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2. Haze attenuation

When visibility is reduced to less than 0.5 km because of dense haze, the case is equivalent to that of thick fog in a temperate region. Attenuation is predicted to high and reaches 155 dB/km. Atmospheric attenuation as a result of haze can be determined by calculating the exponential Beer–Lambert law (Weichel, 1990) as follows:

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

where σ=Scattering coefficient

l=Propagation distance (km)

The attenuation coefficient represents the scattering of laser photons and their interaction with particles suspended in the atmosphere. This scattering can be categorized into three types based on the radius size (r) of particles with respect to laser wavelength (λ) as follows (Achour, 2002):

$r < < \lambda$ Rayleigh scattering

$r \approx \lambda$ Mie scattering

$r > > \lambda$ Non-selective scattering

The size of haze particles varies between 0.01 and 1 µm of radii, which is close to the wavelength applied by FSO. Thus, haze particles are classified under Mie scattering (Kim et al., 2001). The principle behind the use of the visibility sensor equipment to obtain visibility value is based on the sum of the forward directions of all suspended particles along the propagating laser beam. The summation is described by the Mie scattering coefficient and can be expressed in the following equation (Kruse et al., 1962):

$$\sigma = \sum_i n_i\, Q_i\, \pi\, r_i^2 \tag{2}$$

where n_i = distribution of the ith particle

Q_i = Scattering efficiency of the ith particle

Scattering efficiency, radius, and number of particles are parameters that may not always be available, thus rendering the Mie scattering equation impractical (Ijaz et al., 2013; Kim et al., 2001). The empirical equation developed by Kruse, (Kruse et al., 1962) is more practical than the Mie scattering equation. The former is based on the definition of meteorological visual range and experimental data. This formula is a function of visibility V (km) for a given wavelength λ (nm) given by:

$$\sigma = \frac{|\ln(\varepsilon)|}{V}\left(\frac{\lambda}{\lambda_o}\right)^{-q} \tag{3}$$

where ε is the contrast (visible) threshold, λ_o is the maximum spectrum of the solar band or visibility reference and q is the size distribution of the scattering particles. From the definition of visibility (see Section 3); the values of ε and λ_o can be derived as 0.02 and 550 nm respectively. And the value of q has been proposed by Kruse, Kim and Ijaz from Eq. (5), Eq. (6) and Eq. (7) respectively. Substitute Eq. (3) into Eq. (1), the specific atmospheric attenuation can be therefore expressed in the decibel scale by:

$$\tau\,(dB/km) = \frac{17}{V}\left(\frac{\lambda}{550}\right)^{-q} \tag{4}$$

q value is determined based on experimental data. The values of q as obtained from the model developed by (Kruse et al., 1962) are listed as follows:

$$q(V) = \begin{cases} 1.6 & \text{for } V > 50 \text{ km} \\ 1.3 & \text{for } 6 < V < 50 \text{ km} \\ 0.585V^{1/3} & \text{for } 0 < V < 6 \text{ km} \end{cases} \tag{5}$$

Subsequent investigations indicate that the value of q for the equation described above may be incorrect, especially in relation to low visibility because when the value of this factor drops below 0.5 km, such as in the case of fog and dense haze, attenuation is independent of wavelength. Therefore, the aforementioned equation is modified only for low visibility and (Kim et al., 2001) proposed the following model:

$$q(V) = \begin{cases} 0.16V + 0.34 & \text{for } 1 < V < 6 \text{ km} \\ V - 0.5 & \text{for } 0.5 < V < 1 \text{ km} \\ 0 & \text{for } V < 0.5 \text{ km} \end{cases} \tag{6}$$

Although this modified model remains unverified by experiments, it has been used and recommended by many recent studies on FSO (Ijaz et al., 2013). Later study has conducted an experiment at selective wavelengths of 830 nm and 1550 nm and measured attenuation of continual fog as well as visibility data (Nadeem et al., 2010). they observed that 1550 nm has lower attenuation than 830 nm. also they proposed an accurate prediction model compare with Kim model. another study showed that the attenuation due to fog and haze are wavelength dependent (Grabner and Kvicera, 2011). their empirical prediction model can be obtained the attenuation by given liquid water content and estimated effective radius of fog and haze which may not be available all the time. recent study proposed a prediction model based on theory and experiment by observing attenuation of fog and smoke conditions for 600–1600 nm wavelengths (Ijaz et al., 2013). the experiment conducted based on a controlled laboratory condition of fog and smoke. their new proposing model is:

$$q(\lambda) = \begin{cases} 0.1428\lambda - 0.0947 & \text{Fog} \\ 0.8467\lambda - 0.5212 & \text{Smoke} \end{cases} \tag{7}$$

The above model is valid for visibility range of 0.015 km < V < 1 km. the prediction is linked directly with visibility for desire wavelength. also the model is better than Kruse and Kim models in predicting the smoke attenuation. the experimental data of this model found to be with close agreement with Kim model for V > 0.5 km. the argue with Kim model is the value of q especially for V < 0.5 km as well as considering the wavelength.

All the previous models were found to be agreed that Kim model is not accurate in predicting fog and haze attenuation for V < 0.5 km.

3. Visibility measurement

Meteorological visual range or visibility is defined as the maximum distance propagated by a visible 550-nm wavelength optical signal (the maximum sensitivity level of the human eye) while distinguishing dark objects against its background at 2% (Middleton, 1957). In technical terms, this distance is where light loses 2% of its original power (Kim et al., 2001). Another definition suggests that visibility is the distance at which a dark object may be distinguished against the horizon. Initially, visibility is a measure developed for meteorological purposes. Annual measurements have improved, and the accuracy of measurement is ensured. The most popular visibility measurement methods are eye reading and instrumental methods, both of which are applied at

Table 1
Visibility equipment specification.

Items	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