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Analysis of Fog and Smoke Attenuation in a Free Space Optical Communication Link under Controlled Laboratory Conditions

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Abstract—**In this paper, the attenuation of free space optical (FSO) communication systems operating at selected wavelengths of 0.83 µm, 1.31 µm and 1.55 µm in the controlled laboratory based fog and smoke environments are compared. The fog and smoke are generated and controlled homogeneously along the indoor atmospheric chamber of length 6 m. The experimental results from the selected wavelengths are compared for the continuous spectrum range (0.6 µm < λ < 1.55 µm) attenuation. The results show that, unlike the fog attenuation, the resultant smoke attenuation linearly decreases from the visible towards the near infrared (NIR) range from dense to light smoke conditions.**

Index Terms; Free space optics; Fog attenuation; Smoke Attenuation; Visibility

I. INTRODUCTION

FSO is a technology that uses the visible and infrared (IR) light propagating through the atmospheric channel to transmit information. The FSO communications are attracting attention as the contemporary technology to solve the last mile bottleneck issues in local area access networks due to their high bandwidth, low cost implementation in a non-licensed spectrum, relatively lower power consumption and immunity and security compared with RF technologies [1-3]. However, the constitution of the atmosphere, particularly, aerosols (fog, smoke, dust) have similar particle size distributions compared with optical wavelengths in FSO. This can potentially result in scattering and absorption of visible and IR optical beams, thus degrading the FSO link performance and its availability [4, 5]. As a result, the study of the relation between different aerosols particles and wavelength is one of the key subjects in order to characterise the FSO link availability.

The simultaneous study for all the wavelength spectrum range (0.6 µm < λ < 1.55 µm) under real outdoors fog conditions is very difficult to perform [6-8]. This is due to various reasons mainly: (i) the unavailability of the experimental setup for outdoor links due to the long waiting observation time and reoccurrence of dense fog events for visibility ($V < 0.5$ km) and (ii) the difficulty in controlling and characterising the aerosols in the atmosphere due to the inhomogeneous presence of the aerosols along the length of the FSO link. Hence an indoor atmospheric laboratory chamber is designed so that the atmospheric aerosol channel can be controlled; similar to the previous attempt made for controlled atmospheric turbulence studies [9]. Therefore, specific measurements of the visibility and aerosol attenuation can be carried out for each wavelength. Moreover, to the best of our knowledge, there is no experimental data available in diverse smoke conditions which are normal in urban area FSO links.

In this research work, the experimental results for the fog and smoke attenuation at 0.83, 1.31 and 1.55 µm wavelengths for measured visibility ($V < 0.5$ km) are reported. On the other hand, the continuous spectrum attenuation from visible – NIR for the same controlled fog and smoke is measured to validate laboratory-based experimental results for the individual wavelengths. This paper is organised as follows: the characterisation of the fog and smoke attenuation in laboratory chamber is outlined in Section II, whereas the experimental description is explained in Section III. In Section IV the results are discussed. The conclusions are drawn in Section V.

II. CHARACTERISATION OF FOG AND SMOKE ATTENUATION IN LABORATORY CHAMBER:

The link visibility (i.e. the meteorological visual range) is used to characterize the fog and smoke attenuation. Using the Koschmieder law meteorological visibility V (km) can be expressed in terms of the atmospheric attenuation coefficient β_λ and visual threshold T_{th} at 0.55 µm wavelength and is given as [10]:

$$V = -\frac{10\log_{10}(T_{th})}{\beta_\lambda}\ \text{(km)}, \tag{1}$$

where β_λ is normally expressed in (dB/km), and is mathematically defined by knowing the transmittance (T) of the optical signal and the propagation distance (L) using the Beer-Lambert law as [11]:

$$\beta_\lambda = -\frac{10\log_{10}(T)}{4.343L}\ \text{(dB/km)}. \tag{2}$$

Generally, due to the complexity involved in the physical properties of the fog, like particle size and the non-availability of particle distribution, the fog induced attenuation of the optical signal can be predicted using empirical models [12-14]. These models use the visibility data in order to estimate the fog induced attenuation. The original empirical relationship which relates V with the fog attenuation has been given by the Kruse model [13]:

$$V(km) = \frac{10\log_{10} T_{th}}{\beta_\lambda}\left(\frac{\lambda}{\lambda_o}\right)^{-q} \tag{3}$$

where T_{th} is taken as 2%, λ_o is the maximum spectrum of the solar band and q is the coefficient related to the particle size distribution in the atmosphere. The Kruse model estimates the haze attenuation from visible – NIR wavelengths. However, Kim modified the Kruse model using theoretical assumptions for the fog by defining the q value [14]. Therefore, we are using the Kim model in our theoretical analysis, here the values of q indicate that the atmospheric attenuation coefficient β_λ is wavelength independent in fog for $V < 0.5$ km as follows [14]:

$$q = \begin{cases} 1.6 & \text{for } V > 50 \text{ km} \\ 1.3 & \text{for } 6 < V < 50 \text{ km} \\ 0.16V + 0.34 & \text{for } 1 < V < 6 \text{ km} \\ V - 0.5 & \text{for } 0.5 < V < 1 \text{ km} \\ 0 & \text{for } V < 0.5 \text{ km} \end{cases} \quad (4).$$

III. EXPERIMENT DESCRIPTION

The setup used in the laboratory based FSO experiment consists of an optical transmitter end T_x and an optical receiver end R_x separated by the atmospheric chamber, see Fig. 1(a). The controlled channel, represented by the atmospheric chamber has a dimension of 550×30×30 cm^3 as shown in Fig. 1(b) and FSO link length of 6 m. We have selected two types of aerosols using smoke machine (fine dry particles) and fog machine (water steam) with 100% humidity with an output of 0.94 m^3/sec, see Fig. 1(c).

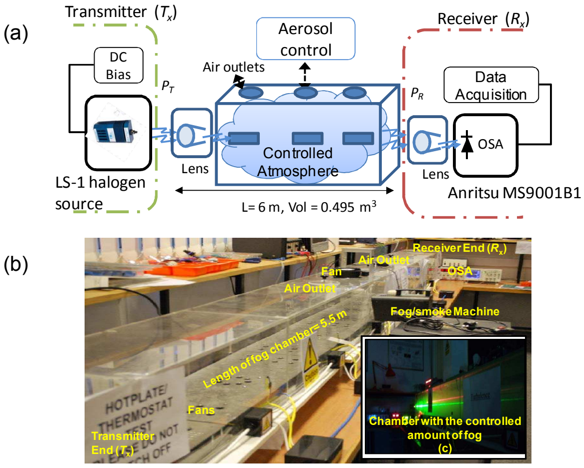

Figure 1. (a) The experimental set up to measure the fog attenuation and visibility, and (b) the laboratory controlled atmospheric chamber and FSO link setup, and (c) inset, the scattering of light due to the smoke in the chamber.

The experiment was carried out using the continuous LS-1 tungsten halogen light source with a broad spectrum optimized for the visible NIR and an optical receiver R_x using an Anritsu MS9001B1 optical spectrum analyzer (OSA) with a spectral response of 0.6 to 1.75 µm. The amount of aerosols in the atmospheric chamber is controlled by fans and the ventilation system. This allowed the fog/smoke particles to settle down homogeneously within the chamber before the acquisition of data. An automatic data acquisition (DAQ) system is developed by connecting the OSA to a computer using GPIB bus and LABVIEW control environment. In order to measure the fog effect on different wavelengths, the average received optical power P_R is measured at R_x before and after the injection of the smoke/fog into the atmospheric chamber. The normalized transmittance T is calculated from P_R with fog to without fog. We measured β_λ using (2) corresponding to the measured T from light to dense fog condition for all wavelengths. The link visibility is measured simultaneously with the β_λ along the length of the chamber at 0.55 µm wavelength using (1). Note that, the goal of the experiment is to characterise the attenuation, identical powers at different wavelengths are not essential. The geometric and the other losses were not taken into account for T_x, as P_R was measured both before and after the fog at R_x to attain the wavelength dependent fog loss.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

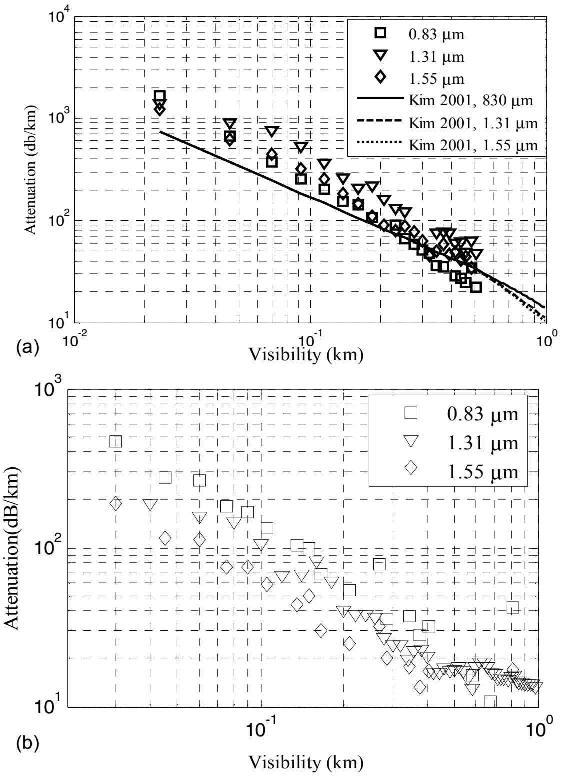

Figure 2. The measured attenuation (dB/ km) and visibility (a) fog and (b) smoke.

Curves of measured fog attenuation (in dB/ km) against the measured visibility for 0.83 µm, 1.31 µm and 1.55 µm wavelengths are shown in Fig. 2(a). We noticed that the measured attenuation is almost identical at 0.83 µm and 1.55 µm for the dense fog condition, i.e., $V < 0.5$ km in accordance with Kim model. However, the measured attenuation at 1.31 µm is higher than at 1.55 µm for $V < 0.5$ km, contradicting the wavelength independency of Kim model. The experimental results show the inconsistent effect of fog attenuation on the selected wavelengths for $V < 0.5$ km. However, the effect of smoke attenuation is found to be linearly decreasing form 0.83 µm to 1.55 µm from very dense smoke ($V < 0.07$ km) to moderate smoke ($V < 0.5$ km) as shown in Fig. 2(b). This clearly demonstrate the dependency of wavelength on attenuation as the smoke attenuation values are 1000 dB/ km and 400 dB/ km for 0.83 µm and 1.55 µm at $V = 0.02$ km, respectively. Fig. 2(b) depicts that selection of 1.55 µm is more favourable in dense ($V < 0.07$ km) to moderate smoke ($V = 0.5$ km) smoke conditions.

Fig. 3(a) shows the received power for the visible – NIR spectrum using the controlled smoke and fog in the atmospheric chamber. The measured received power (P_r) for the visible range is -25 dBm, decreasing to – 30 dBm for the NIR range of the spectrum for the clear channel condition (reference). However, in the case of thick and dense smoke conditions, the visible range attenuates more than the NIR range. The received power has a sudden drop from – 25 dBm to -55 dBm for the visible range of the spectrum increasing at 1.55 μm for the dense smoke condition. The corresponding spectrum loss for the dense smoke condition is about 30 dB for the visible spectrum range decreasing to about 7 dB for 1.55 μm (see Fig. 3(b)).

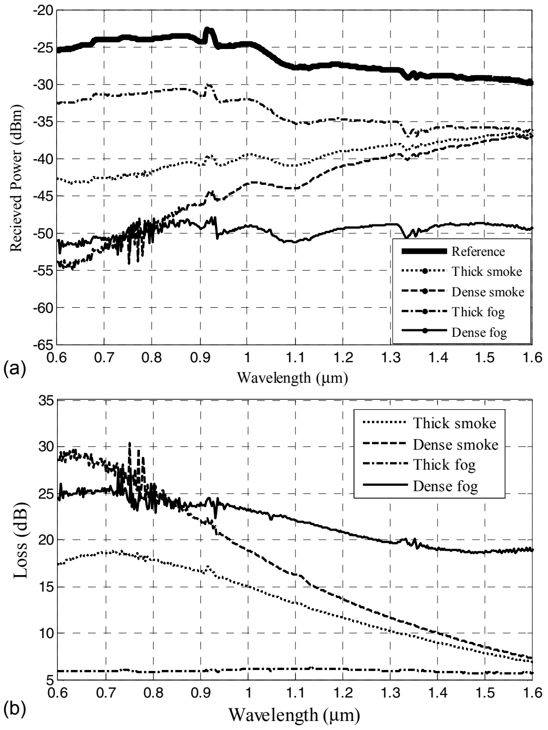

Figure 3. (a). Measured received power for the visible – NIR spectrum for smoke and fog conditions, and (b) measured loss for smoke and fog.

However, the received power is -43 dBm for the thick smoke condition at the visible range and tails towards -37 dBm for the NIR range (1.55 μm). The corresponding loss for the thick smoke condition is ~ 17 dB for the visible spectrum range decreasing to 7dB towards the 1.55 μm as shown in Fig. 3 (b). This result clearly shows that the spectrum loss decreases almost linearly from 0.6 μm towards the 1.55 μm wavelengths. However, at the presence of fog, the received power is almost – 51 dBm for the visible spectrum and -49 dBm for the NIR range of the spectrum for the dense fog. The corresponding loss for the dense fog condition is 25 dB for the visible spectrum and tails to ~ 21 dB for the NIR spectrum (see Fig. 3(b)). However, for the thick fog conditions, the spectrum loss is ~ 6 dB from visible – NIR spectrum, verifying the wavelength independent fog attenuation for the spectrum range (0.6 μm < λ < 1.5) comparing with the smoke attenuation.

V. CONCLUSION

In this paper, we have demonstrated the impact of fog and smoke on the FSO link performance under the laboratory controlled conditions.We have verified that the fog attenuation is not wavelength dependent for the spectrum range of 0.6 μm < λ < 1.5 μm under a controlled fog condition for $V < 0.5$ km. This validates that the fog attenuation is more likely to be locally dependent on the atmosphere. However, unlike fog attenuation, the attenuation due to smoke is almost linearly decreasing toward the NIR wavelengths.

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