Experimental Study of Atmospheric Visibility and Optical Wave Attenuation for Free-Space Optics Communications

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Abstract

Optical wave attenuation due to low atmospheric visibility conditions causes a performance degradation of free-space optical (FSO) communication systems. Both visibility and attenuation are measured on a 100-meter long experimental free space optical link operating with a wavelength of 830 nm. Meteorological conditions causing particular attenuation events are identified. Available models of the relation between atmospheric visibility and optical attenuation are compared with the measured data. It is shown that classical models widely used in the FSO community still underestimate optical attenuation at medium and low visibility conditions.

1. Introduction

Free-space optical (FSO) communication systems [1, 2] are becoming more widespread in wireless communications nowadays. Both their low cost and a lack of stringent regulatory requirements are the major reasons for their popularity. They utilize optical signal transmissions in a free space, through the atmosphere. The optical signal is transmitted from the fixed transmitter to the receiver through the atmosphere, which is an inhomogeneous medium varying in time. Characteristics of this medium relate to one of the most serious concerns about free-space optical communication links, which is their availability. It is known that the availability performance of FSO links is significantly limited by the propagation conditions in the atmosphere. It appears that electromagnetic waves in the optical region are strongly attenuated in the direction of optical beam propagation by scattering and absorption processes in the atmosphere. Fog events and strong snow events are the most adverse weather conditions because they result in a high specific attenuation of optical waves. Since the fade margin of current FSO systems reaches a maximum of several tenths of a dB (eye safety requirements), the systems can easily become unavailable when communication is interrupted. It follows that the higher the occurrence rate of such adverse propagation conditions, the lower the availability time of the system that can be reached.

In meteorology, there is an important concept of atmospheric visibility. Measured time series of visibility can be used for the performance availability prediction of FSO systems. The relation between visibility and optical attenuation has to be known for this purpose. In this paper, several available models are assessed in light of data obtained from a recent simultaneous measurement of both visibility and optical path attenuation carried out in Prague. Recently-proposed models that are adjustable by their parameters to fit measured data for specific climatic conditions are also included .

2. Atmospheric Visibility and Optical Attenuation

Atmospheric visibility is a useful measure of the atmosphere containing fog, smog, dust, smoke and other contaminating particles. A widely-used definition known as the meteorological optical range (MOR) is given as the “length of path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp at a color temperature of 2700 K to 0.05 of its original value”. Atmospheric visibility is usually measured at airports so it is possible to obtain visibility characteristics in areas where the FSO systems are to be deployed. In order to predict the optical attenuation statistics from the visibility statistics and estimate the availability of an FSO system, the relation between visibility and attenuation has to be known. In the following, specific attenuation A (dB/km) characterizes the attenuation of an optical signal propagating in a medium of unit length:

$$A = (1/d)10\log\left(P(\lambda,0)/P(\lambda,d)\right) = (1/d)10\log\left(e^{\gamma(\lambda)d}\right) = 10\log(e)\gamma(\lambda), \qquad (1)$$

where λ (nm) is the wavelength, $P(\lambda,0)$ is the optical power emitted from the transmitter (without attenuation) at zero distance, $P(\lambda,d)$ is the optical power measured at distance d (km) and $\gamma(\lambda)$ denotes the total extinction coefficient per unit length which represents the attenuation of light. Relation (1) is generally valid for attenuation events caused by different mechanisms like molecular and gas absorption. However, only attenuation due to fog is analyzed in this paper. Long-term experiments as well as theoretical considerations [3] confirm that fog induces the greatest path attenuations and the longest outages on the FSO links.

Several models describing the relationship between visibility and optical attenuation due to fog were published in literature [4-6]. The Kruse [4] and Kim [5] models were originally derived based on the visibility definition for a wavelength of 0.55 μm and a power ratio of 0.02 (different from MOR). Al Naboulsi [6] models were obtained by interpolating results from FASCOD software. Another simple approach for attenuation vs. visibility modeling was proposed recently [7]. Two empirical models were given – the *power-law model* and the *inhomogeneous model*. Both are intended to fit the measured data in order to improve the performance of previous non-parameterized models. In the power-law model the specific attenuation A (dB/km) is calculated using the following equation:

$$A = 10\log(\mathrm{e})\, aV^{b} + (c), \tag{2}$$

where V (km) is atmospheric visibility. In the special case where parameters $a = 3$ and $b = -1$ it reduces to the Kruse model for a fixed wavelength of $\lambda = 550$ nm. An additional shift parameter c in brackets in equation (2) can be used to further improve a model fit (*the shifted power-law model*) as will be demonstrated in Section 4. The inhomogeneous model started from the assumption of the linear spatial dependence of visibility $V(x)$ (and therefore attenuation) along the propagation path. It is defined as the mean value of specific attenuation along the propagation path:

$$A = (1/d)\int_0^d A(x)\mathrm{d}x = (1/d)10\log(\mathrm{e})\int_0^d (3/V(x))\,\mathrm{d}x, \quad V(x) = V_0 + (aV_0 + b)x \tag{3}$$

with parameters a, b and V_0 denoting visibility at one site of the propagation path.

3. Measurement

An experimental FSO link with a wavelength of 830 nm operates on a 100 meter-long path in Prague, the Czech Republic and is located at an approximate height of 26 meters above ground level (see Figure 1). The transmitted optical power is 30 dBm, the diameter of the Fresnel lens is 15 cm. The real optical fade margin at our disposal is about 20 dB. That means it is possible to measure specific attenuation up to a value of 200 dB/km. Optical calibration was performed before deploying the device. The calibrated Received Signal Strength Indicator (RSSI) signal of the FSO link has been recorded continuously on a PC hard disc. The relative received signal level was derived from the RSSI signal and processed statistically. Attenuation events were classified according to meteorological conditions causing a corresponding attenuation event.

Figure 1. a) Experimental free space optical link on the rooftop of TESTCOM (left), b) video camera image of the FSO link location, 3 Jan 2007, clear atmosphere (center), c) fog event on 16 Nov 2006 (right).

Meteorological conditions were identified by means of video camera images (see Figure 1) and data obtained from an automatic meteorological station. Both the camera and the station are located near the optical receiver site. The automatic meteorological station is equipped with VAISALA sensors for the measurement of temperature, humidity and air pressure, wind velocity and direction, and two tipping-bucket raingauges with different collector areas for the measurement of rain intensities. The VAISALA PWD 11 equipment measures the visibility (MOR) up to 2000 m using forward scattered light at an angle of 45°. The distance between the transmitter and the receiver of the visibility detector is about 0.5 m, hence the measurement is very local. Meteorological conditions during fading events were recorded. The calibrated RSSI signal was continuously recorded.

Figure 2 shows the measured time series of attenuation and visibility during two days in October 2007 and January 2008. Long-term fog events caused significant attenuation of the optical path. One can notice the rapid change of attenuation when the fog was arriving and leaving the propagation path. This complicates the investigation into the visibility vs. attenuation relationship because in this case the good time synchronization of both of the time series is needed to keep errors small. Perfect synchronization is not possible because visibility is only measured in one minute intervals (one minute integration) by the PWD11 detector.

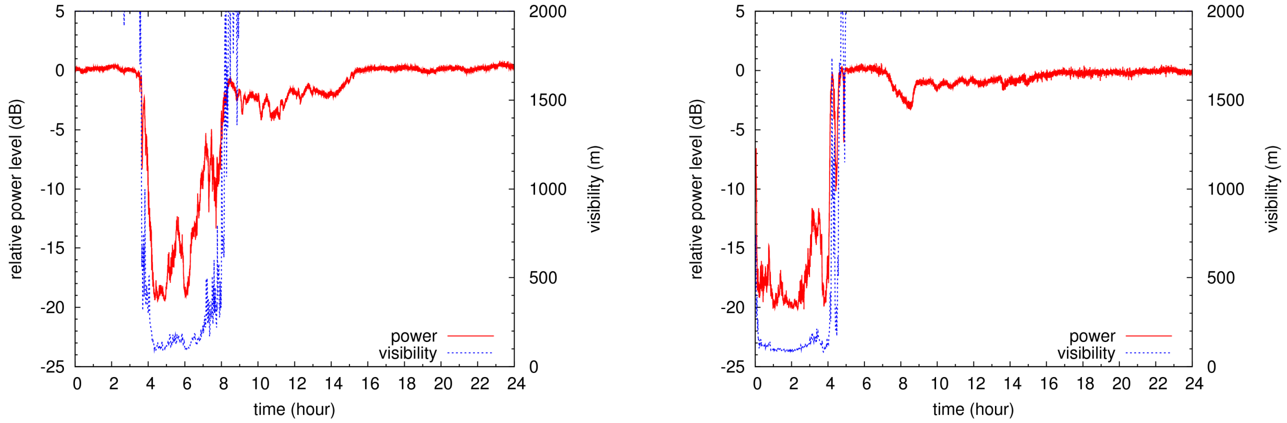


Figure 2. Relative received signal level and atmospheric visibility measured on 28 Oct 2007 and 14 Jan 2008.

4. Results

The measured data was processed to obtain the visibility vs. attenuation dependence during the days with fog events. It is seen from Figure 3 low visibility data generally prevails because fog events appear and disappear steeply.

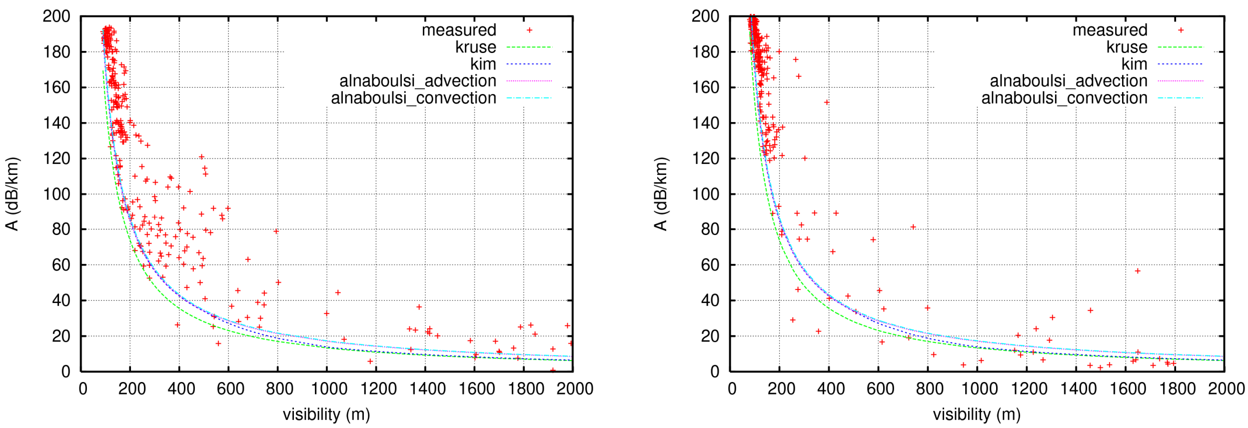
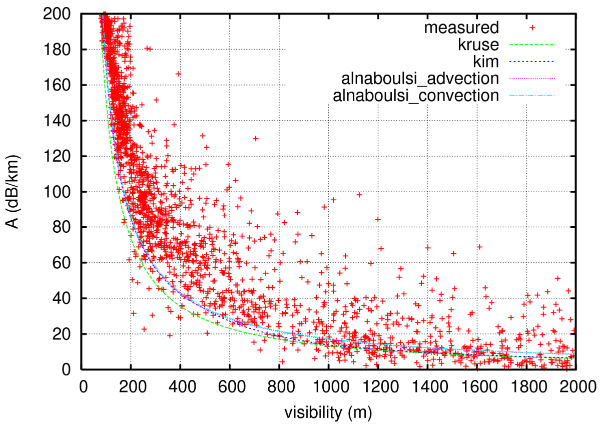


Figure 3. Comparison of visibility vs. attenuation models and measured data on 28 Oct 2007 and 14 Jan 2008.

In order to compare a reasonable amount of data, measured time series from 5 foggy days (19/11/2006, 28/12/2006, 28/10/2007, 2/1/2008 and 14/1/2008) were processed together and the results obtained are shown in Figure 4. The Kruse, Kim and Al Naboulsi models underestimate attenuation values in the region of medium and lower visibilities. The performance of these models is good for visibilities higher than 1 km. The power-law model, inhomogeneous model and shifted power-law model were fitted resulting in following root mean square errors: RMS(Kruse) = 21.14 dB, RMS(Kim) = 17.16 dB, RMS(Al Naboulsi advection) = 16.95 dB, RMS(Al Naboulsi convection) = 16.55 dB, RMS(power-law) = 14.77dB, RMS(inhomogeneous) = 15.72 dB and RMS(shifted power-law) = 11.98 dB. The shifted power-law model (equation (2)) is the best one with respect to RMS and it performs better mainly in the region of medium visibilities. The resulting parameters of this model are $a = 6.861$, $b = -0.858$, $c = -10.428$.



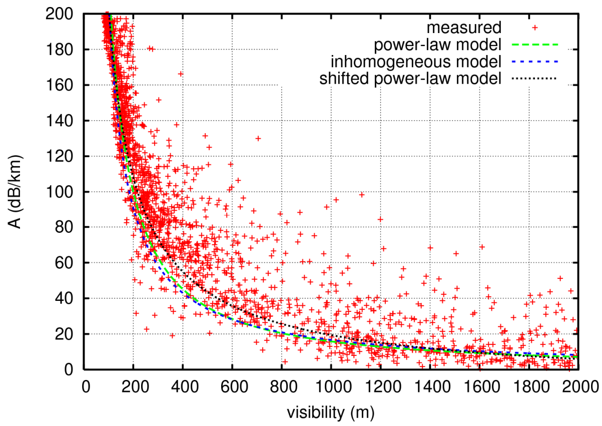


Figure 4. Comparison of visibility vs. attenuation models and measured data from 5 foggy days between November 2006 and January 2008, non-parameterized models (left) and fitted models (right).

5. Conclusion

The measurement of atmospheric visibility and optical path attenuation was described. The available models of the relationship between visibility and attenuation due to fog were evaluated using measured data. Standard models give slightly lower estimates of attenuation for visibilities lower than 1000 meters. New parametric models can be used in order to obtain more realistic estimates. These empirical models are intended to fit site-dependent measured data. If the visibility vs. attenuation models are utilized for the prediction of FSO link availability statistics from visibility statistics, statistical errors are inherent in the procedure which is clear from the data variance in the scatter plots in Figures 3 and 4. Furthermore, there are also other attenuation mechanisms – particularly absorption by snow which impairs the FSO links significantly. These were not considered in the paper, but should be kept in mind if realistic availability statistics are to be obtained.

6. Acknowledgments

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7. References

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