Channel Modeling for Terrestrial Free Space Optical Links

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ABSTRACT

With recent advances and interest in Free Space Optics (FSO) for commercial deployments, a proper understanding of optical signal propagation in different atmospheric conditions has become essential, and thus arises the need to rationalize the effects of atmospheric channel on terrestrial FSO links. In this paper, we present the preliminary results of our effort to simulate the atmospheric free space terrestrial optical channel with precise mathematical models of the most deterrent attenuators. Attenuations due to fog, rain, snow and scintillation are considered. Thus, the channel model acquired is a first step towards developing a comprehensive model predicting the performance of a terrestrial FSO link operating under natural weather conditions.

Keywords: Free Space Optics (FSO), atmospheric attenuations, channel modeling, optical propagation, scintillation losses.

1. INTRODUCTION

The concept of transmitting information through the air by means of a modulated light signal is quite old, and although significant advances have been made over the past 10 years, the concept remains relatively simple: a narrow beam of light is launched at a transmission station, transmitted through the atmosphere, and subsequently received at the receiving station [1]. The advances in the technology, now referred too as FSO, have come about in response to a need for greater bandwidth and improved communication systems. Free space optical communications has attracted a considerable attention for a variety of applications in the field of telecommunications. FSO applications span over a wide range from satellite links to robotics and generates interest for several distinct markets, namely: the last mile high bandwidth internet connectivity, the temporary high bandwidth data links, the mobile telephony backhaul (3G), satellite links as well as the various applications where the optical fibres cannot be used. In spite of the possibility of different applications, the terrestrial FSO links still remains of primary significance and the performance of such links is highly dependent on different weather conditions particularly in presence of fog. Severity and duration of the atmospheric effects affect the distance and the availability of the links. Thus, the interest aimed at this technology has developed the need to understand the effects of various weather conditions on the optical radiation propagation in the atmosphere. In general, weather and installation characteristics that impair or reduce visibility also effect the FSO performance. The effort here is to focus on some of the more important atmospheric attenuators and to simulate their attenuation behavior using precise mathematical relations, derived and improved over the years. A conscious effort has been made to select the best known and most suitable relations in modeling the FSO channel. Previously, a significant effort in this regard has been made by M. Achour [2, 3]; but much more is desired as to the best of our knowledge comprehensive channel models for terrestrial FSO communications still have many unanswered questions.

2. CHANNEL MODELING

Modeling the channel for terrestrial FSO is a problem of considerable complexity due to the variety of impairments possible and the disagreement over the mathematical modeling of the various phenomena. FSO links are impaired by absorption and scattering of light by earth's atmosphere. The atmosphere interacts with the light due to the composition of the atmosphere, which normally consists of a variety of different molecular species and small suspended particles called aerosols. This interaction produces a variety of phenomena: frequency selective attenuation, absorption, scattering and scintillation. In addition, sunlight can affect FSO performance when the sun is colinear with the free space optical link. Frequency selective absorption at specific optical wavelengths comes from the interaction between the photons and atoms or molecules that leads to the extinction of the incident photon, elevation of the temperature, and radiative emission. Atmospheric scattering results from the interaction between the photons and the atoms and molecules in the propagation medium. Scattering causes angular redistribution of the radiation with or without modification of the wavelength. Scintillation is caused by thermal turbulence within the propagation medium that results in randomly distributed cells. These cells have variable sizes (10 cm – 1 km), temperatures, and refractive indices causing scattering, multipath and variation of the angles of arrival. As a result, the received signal amplitude fluctuates at frequencies ranging between 0.01 and 200 Hz. In addition, scintillation can cause wave front distortion resulting in defocusing of the beam.

3. SIMULATING FSO SYSTEMS

The following input parameters of the simulation model are used: the transmitter is described by the transmitted power P_{trans} [mW], the diameter of the active area is $d_{transmitter}$ [mm], the opening angle of the beam FOV (field of view) is θ [mrad], the transmitted wavelength is λ [nm] and the optical losses at the output of the transmitter are P_{opt} [dB]. At the receiver the diameter of the receiving surface is of main interest and is described by $d_{receiver}$ [mm]. The geometrical losses P_{geo} [dB] are calculated as in equation (1). Fig. 1 shows the available input power for the receiver. Further the channel-length l [m] can be chosen in the simulation tool. The weather influences for the channel are simulated for the used wavelength. For the fog simulation, the Kim and Kruse model are used. Additionally, rain or snowfalls are catered in the simulation. The snow behaves differently if it's dry or wet, both scenarios are considered. A supplemented tool (Slider) deals with atmospheric turbulences (they can differ between low and high). The visibility value can be used from the reference or it can be varied.

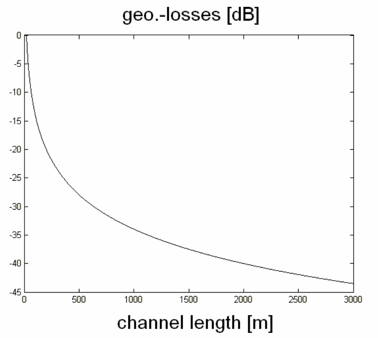


Fig. 1.

$$P_{geo} = 10 \cdot \log\left(\frac{d_{receiver}}{d_{transmitter} + l \cdot \theta}\right)^2 \quad [dB] \qquad (1)$$

4. ATTENUATION MODELING

The terrestrial FSO links must deal with the atmosphere just above the surface of the earth, where it has maximum density due to the gravitational force. Mie scattering due to aerosol and fog droplet distribution; which is by far the most complex to simulate; is considered the major atmospheric element that attenuates the optical signal.

4.1 Fog Attenuation

The theoretical background of fog attenuation for light based on Mie Scattering can be found in [4-6] and is not being dealt with here. Several models exist which allow to calculate specific attenuation for different optical wavelengths based on visibility data. The two most widely used models that we used and implemented in our simulation are the Kruse model and the Kim model. The specific attenuation is calculated in equation (2), with the variables visibility V [km], wavelength λ [nm], visibility reference at wavelength λ_0 [nm] and for transmission of air drops to V% percent of the clear sky; and the results are shown in figure 2. The wavelength dependency in this expression is expressed by q, which is in the Kruse model given by equation (3) and in the Kim model by equation (4). At very high attenuations the Kim model is the better model.

$$a_{spec} = \frac{10 \log V_{\%}}{V[km]}\left(\frac{\lambda}{\lambda_0}\right)^{-q} \quad [dB/km] \qquad (2)$$

$$q = \begin{cases} 1.6 & if \quad V > 50\,km \\ 1.3 & if \quad 6\,km < V < 50\,km \\ 0.585V^{1/3} & if \quad V < 6\,km \end{cases} \qquad (3)$$

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

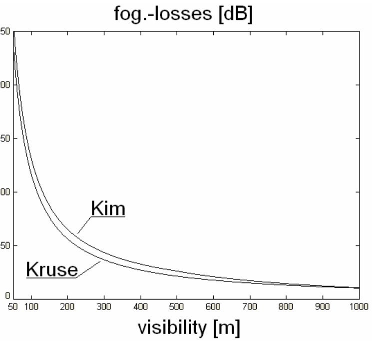


Fig. 2.

4.2 Rain Attenuation

Rain is also an important attenuator for the optical signals and the specific attenuation for rain has been modelled as in equation (5) [7] where the rain rate is given by R [mm/h] and the dependence is drawn in figure 3.

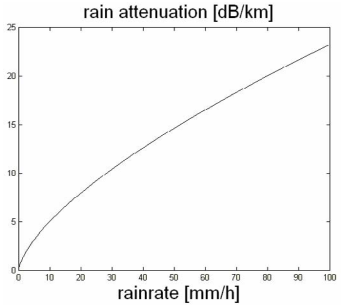


Fig. 3.

$$a_{rain} = 1.076\, R^{2/3} \quad [dB/km] \tag{5}$$

4.3 Snow Attenuation

The attenuation due to snow fall has been modelled based on dry or wet snows and the specific attenuation is given by equation (6) where S is the snow rate in [mm/h]. The Parameters a and b are given for dry snow in equation (7) and for wet snow in equation (8) where λ represent the transmission wavelength in [nm]. Figure 4 depicts the difference between wet and dry snowfall.

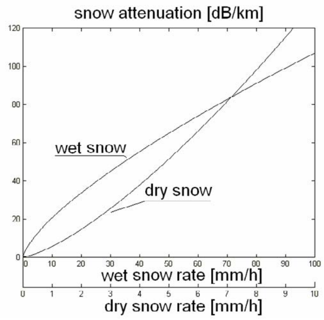


Fig. 4.

$$a_{snow} = a \cdot S^{b} \quad [dB/km] \tag{6}$$

$$a = \; 5.42 \cdot 10^{-5} \lambda + 5.4958776 \qquad b = 1.38 \tag{7}$$

$$a = 1.023 \cdot 10^{-4} \lambda + 3.7855466 \qquad b = 0.72 \tag{8}$$

5. SCINTILLATION LOSSES

Randomly distributed cells are formed under the influence of thermal turbulence inside the propagation medium; the wave fronts vary causing the focussing and defocusing of the beam. Such fluctuations of the signal are called scintillations. The amplitude and frequency of scintillations depend on the size of the cells compared to the beam diameter [8]. The intensity and the speed of the fluctuations (scintillations frequency) increase with wave frequency. For a plane wave, a low turbulence and a specific receiver, the scintillation variance can be expressed as in equation (9) where λ represent the transmitter wavelength in [nm], l the channel-length in [m] and Cn^2 the refractive index structure parameter in [$m^{-2/3}$]. Cn^2 is for low turbulence 10^{-16}, for moderate turbulence 10^{-14} and for high turbulence 10^{-13} [9]. The dependence from Cn^2 is depicted in figure 5. For strong turbulences, a saturation of the variance given by above relationship is observed. The parameter Cn^2 does not have the same value at millimetre waves and at optical waves. Millimetre waves are especially sensitive to humidity fluctuations while in optic, refractive index is a primary function of the temperature.

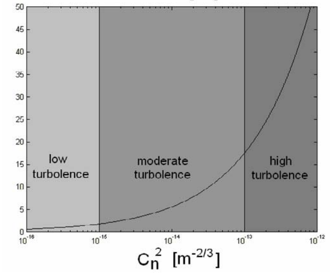
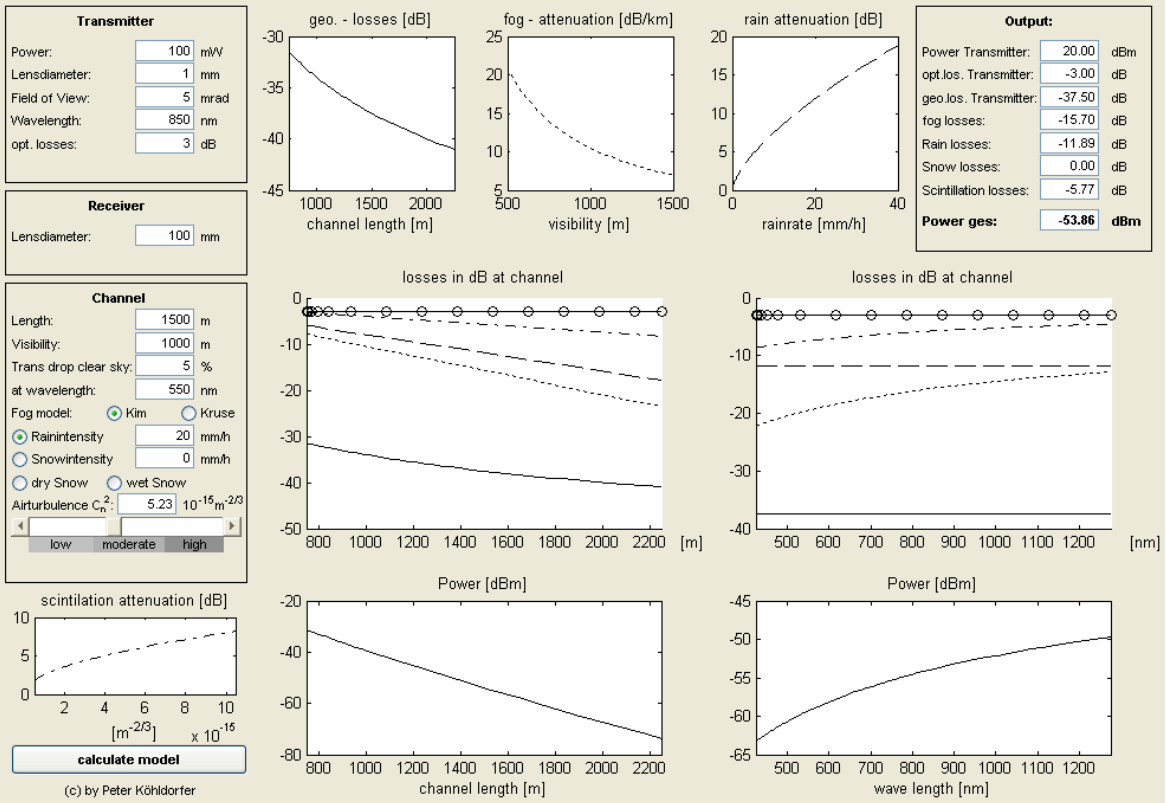


Fig. 5.

$$a_{scin} = 2\sqrt{23.17 \cdot \left(\frac{2\pi}{\lambda} 10^{9}\right)^{7/6} \cdot C_n^2 \cdot l^{11/6}} \quad [\mathrm{dB}] \tag{9}$$

6. GRAPHICAL USER INTERFACE

Figure 6 shows the Graphical User Interface (GUI) of our channel model; in the last two plots in figure 6 the "Power" represents the available input power for the receiver. Much more sophistication is of course possible, and there are ideas to include background ambient light in the future, as well as to produce a probability of error estimation. This model can provide the basic platform to carry on further investigations and to the ultimate goal of achieving a well-formulated channel model for FSO, comparable to the existing RF models.



Transmitter
Power: 100 mW
Lensdiameter: 1 mm
Field of View: 5 mrad
Wavelength: 850 nm
opt. losses: 3 dB

Receiver
Lensdiameter: 100 mm

Channel
Length: 1500 m
Visibility: 1000 m
Trans drop clear sky: 5 %
at wavelength: 550 nm
Fog model: ● Kim ○ Kruse
● Rainintensity 20 mm/h
○ Snowintensity 0 mm/h
○ dry Snow ○ wet Snow
Airturbulence C_n^2: 5.23 $10^{-15} m^{-2/3}$

Output:
Power Transmitter: 20.00 dBm
opt.los. Transmitter: -3.00 dB
geo.los. Transmitter: -37.50 dB
fog losses: -15.70 dB
Rain losses: -11.89 dB
Snow losses: 0.00 dB
Scintillation losses: -5.77 dB
Power ges: -53.86 dBm

Fig. 6.

7. CONCLUSIONS

The channel modeling effort that we have presented in this paper is the first real attempt towards availability and reliability prediction of terrestrial FSO links through simulation. Molecular absorption is a selective phenomenon which results in a spectral transmission of the atmosphere presenting transparent zones, called atmospheric transmission window, and opaque zones, called atmospheric blocking windows, which have not be considered in this model. The model provides the basic tool to do further detailed investigations in terrestrial FSO applications, and can be improved and utilised for a variety of applications. We are also trying to validate the model by practical attenuation measurements that we perform on our installed FSO systems in Graz.

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