Outdoor Wireless Optical Communication System Attenuation at Different Weather Conditions

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Abstract- The effect of visibility range on the atmospheric attenuation of the outdoor wireless optical communication system is studied. The atmospheric attenuation of laser beam in very clear weather, clear weather, light haze, haze, thin fog, light fog, thick fog and dense fog are tested to find their effects on the system availability. The wavelength effect on the atmospheric attenuation is also investigated. The study is focused on the 0.78, 1.3 and 1.55 µm operating wavelengths.

Keywords: atmospheric attenuation, weather conditions, system availability, free space optics, visibility range.

1. Introduction

As demand on deliverable bit rate to end-user continuously increases, conventional radio frequency (RF) technologies find themselves incapable of meeting these requirements. The optical spectrum has long been considered one of the most promising candidates for providing the required bandwidth both for indoor and outdoor applications. Outdoor wireless optical links commonly known as Free Space Optics (FSO) are continuously finding their ways into networks, offering bandwidths unmatched by any of the current RF technologies. However, their weather related availability poses a constraint on their deployment in locations where a high degree of reliability is required [1]. FSO has been attracting an increasing attention in the recent years due to its potential for providing broadband wireless communications. FSO has inherent attributes which make it attractive for communication applications. But, sometimes FSO link availability is low because of atmospheric attenuation and its dependency on weather conditions. So, the main challenge for FSO is atmospheric attenuation. Special attention has been paid to ways in which adverse weather conditions and background radiation affect transmission through the atmosphere. As a result of these effects, the performance of laser communication systems is extremely dependent on the laser transmission wavelength.

2. Outdoor Wireless Optical Communication

The two basic subsystems of OWC are the transmitter and the receiver, Fig. 1. The transmitter converts the electronic signal to light. Light propagates through the atmosphere to the receiver, which converts the light back to the electronic signal. The transmitter includes a modulator, a laser driver, an LED or laser, and a telescope.

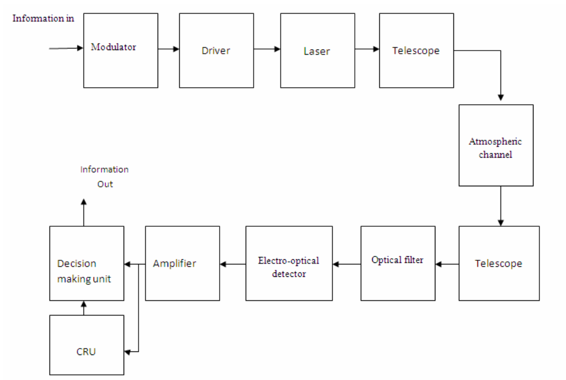

Fig.1 Block diagram of outdoor WOC.

The modulator converts bits of information into signals in accordance with the chosen modulation method. The driver provides the power for the laser and stabilizes its performance, and neutralizes such effects as temperature and aging of the laser or LED. The light source converts the electrical signal to optical radiation. The telescope aligns the laser/LED radiation to a collimated beam and directs it to the receiver. The receiver includes a telescope, a filter, a photodetector, an amplifier, a decision device, and a clock recovery unit. The telescope collects the incoming radiation and focuses it onto the filter. The filter removes background radiation (e.g. sunlight) and allows only the wavelengths of the signal to pass through. The photodetector converts the optical radiation to an electronic signal, and the amplifier amplifies the electronic signal. The decision unit determines the nature of the bits of information based on the time of arrival and the amplitude of the pulse.

The clock recovery unit operates in parallel to the decision making unit and synchronizes the 129 data sampling to the decision making process [2].

A practical example of a basic outdoor OWC has the schematic structure shown in Fig. 2. At the transmitter, a laser beam is generated by an electric-to-optic process and is expanded and directed by a transmitting telescope. After propagation through the atmosphere, it is collected by a receiver telescope, optically filtered and concentrated onto the focal plane detector, and, finally, converted into an electric current by a reverse optic-to-electric process [3].

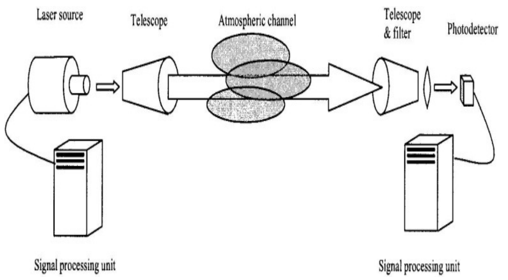

Fig. 2 Schematic structure of a WOC system.

3. Mathematical Model
3.1 Atmospheric Attenuation

When the laser beam propagates through air, it is exposed to attenuation depending on the weather conditions. Optical beam experiences interaction with the medium particles and the particles concentration affects the light beam by absorption (attenuation). Assume that particles may be described as having an absorption cross section area, *σ*, perpendicular to the path of light through a solution, such that a photon of light is absorbed if it strikes the particle, and is transmitted if it does not.

Define z as an axis parallel to the direction that photons of light are moving, and A and dz as the area and thickness along the z axis of a 3-dimensional slab of space through which light is passing. We assume that dz is sufficiently small that one particle in the slab cannot obscure another particle in the slab when viewed along the z direction. The concentration of particles in the slab is represented by N [4]. It follows that the fraction of photons absorbed when passing through this slab is equal to the total opaque area of the particles in the slab, $\sigma\, A\, N\, dz$, divided by the area of the slab A, which yields $\sigma\, N\, dz$.

Expressing the number of photons absorbed by the slab as dI_z, and the total number of photons incident on the slab as I_z, the fraction of photons absorbed by the slab is given by

$$\frac{dI_z}{I_z} = \sigma N d_z \quad (1)$$

The solution to this simple differential equation is obtained by integrating both sides to obtain I_z as a function of z

$$\ln\left(I_z\right) = -\sigma NZ + C \quad (2)$$

where C is integration constant.

The difference of intensity for a slab of real thickness ℓ is I_0 at $z = 0$, and I_1 at $z = ℓ$. Using Eq. (2), the difference in intensity can be written as

$$\ln(I_0) - \ln(I_1) = (-\sigma 0Z + C) - (-\sigma lZ + C) = \sigma lN \quad (3)$$

Rearranging yields

$$T = \frac{I_1}{I_0} = e^{-\sigma lN} = e^{-\sigma' l} \quad (4)$$

where T is the transmission coefficient, I_l is the light beam intensity at $z = l$, I_0 is the light beam intensity at z = 0, L is the path length (distance between transmitter and receiver), σ' is the atmosphere attenuation or total extinction coefficient.

The transmission (or transmissivity) is expressed in terms of an absorbance, σ', defined as [4]

$$F_l = -10\log\left(\frac{I_1}{I_0}\right) = 10\log\left(\frac{p_{receiver}}{p_{total}}\right) = -10\log\left(e^{-\sigma' l}\right) \quad (5)$$

where F_l is attenuation in dB, $P_{receiver}$ is the received power in Watt, P_{total} is the transmitted power in Watt.

The total extinction coefficient σ can be divided into four parts

$$\sigma' = \alpha_m + \alpha_a + \beta_m + \beta_a \quad (6)$$

where α_m is the molecular absorption coefficient, α_a is the aerosol absorption coefficient, β_m is the molecular or Rayleigh scattering coefficient and β_a is the aerosol or Mie scattering coefficient.

It is common to choose a laser wavelength that makes the gas absorption and molecule scattering negligible. For wavelengths between the visual band and 1.5 µm, the molecular absorption, aerosol absorption and the molecular scattering are ***small*** compared with the aerosol scattering, which ***dominates*** the total extinction coefficient.

The meteorological visual range can be obtained from its extinction coefficient β at the reference wavelength (500 nm) as follows [1]

$$v = \frac{\ln(0.02)}{\beta(\lambda = 550nm)} = \frac{3.91}{\beta(\lambda = 550nm)} \quad (7)$$

The attenuation is related to wavelength and visibility can be obtained from Eq. (6)

$$\sigma = \beta_a = \frac{3.91}{v}\left(\frac{\lambda}{550nm}\right)^{-q} \quad (8)$$

where v is the visibility in km, λ is the wavelength in nm, q is the size distribution of the scattering particles {=1.6 for high visibility (V > 50 km , =1.3 for average visibility (6 km < V < 50 km and = 0.585 $v^{1/3}$ for low visibility (V < 6 km [5]).

3.2Visibility

There is three fundamental definitions of visibility: the maximum range at which a dark object can be perceived against the horizon at daytime, the maximum range at which a given light source can be perceived at night time, and the range at which the image contrast drops to 0.02. Only the last one of the three is quantifiable and is defined as

$$v = \beta^{-1}\ln\left(1/_{0.02}\right) = 3.912/_{\beta} \quad (9)$$

where β is the scattering coefficient.

Measurements of the visibility are performed at airports all over the world with good resolution. This visibility information will help to calculate channel availability.

This model is important to help in predicting the WOC system availability as the availability is a function of atmospheric attenuation. So, decreasing the attenuation will result in an increase in the availability of outdoor WOC in low visibility range weather conditions [6].

4. Results and Discussion

4.1 Introduction

Based on the described mathematical model, for atmospheric attenuation of outdoor wireless optical channel, the studied parameters include the visibility range and the operating wavelength in different weather conditions. The simulation calculations (to get the atmospheric attenuation) were performed for several standard international visibility code weather conditions and precipitation.

In this section, we will discuss the atmospheric attenuation due to weather conditions as function of visibility on each weather condition. Visibility values can be practically obtained from air ports measurements or purchased from specific internet sites specialized on climate research but in the present simulation, we assume random samples of the visibility on each weather condition on the predefined visibility range according to international categorization of weather conditions. This is illustrated in Table 1

Visibility range	Weather condition
50 km	Very Clear weather
18.1 km	Clear weather (with drizzle at a 0.25 mm/h rate)
5.9 km	Light Haze (with light rain at a 2.5 mm/h rate)
2.8 km	Haze (with medium rain at a 12.5 mm/h rate)
1.9 km	Thin Fog (with heavy rain at 25 mm/h rate)
770 m	Light Fog (with cloud bursts of 100 mm/h)
200 m	Thick Fog (without rain)
50 m	Dense Fog (without rain)

Table 1 Weather condition and visibility range.

We assumed 500 random samples of visibility values on each weather condition range. Then, we simulate the atmospheric attenuation on each corresponding visibility value, and then calculate the moving average for all the 500 samples at the operating wavelengths 0.78 µm and 1.55 µm.

Our simulation program was run on 1 km link distance and was developed by a Matlab 7 program and Monte Carlo simulation method based on the mathematical model described in section 3. The simulation covers the atmospheric attenuation on all weather conditions mentioned before. In order to expect the outdoor wireless optical system availability we find solutions to mitigate the effect of the weather conditions on the system performance. Also, this simulation can be used for system bandwidth analysis to control the system applications.

4.2 Very clear weather

One of the outdoor wireless optical communication system challenges is its system availability in different weather conditions. The first weather condition we discuss is the very clear weather condition, where the visibility is in a very high range, which can reach 50 km.

The laser beam attenuation per kilometer in a very clear weather is drawn with respect to the 1.55 μm operating wavelength in Fig. 3. We note that the atmospheric attenuation decreases with the visibility. Results for other wavelengths show that the atmospheric attenuation at 1.55μm is greater than that at 0.78 μm. The average attenuation in very clear weather at 0.78 μm is around 0.2 dB/km. The corresponding value at 1.55μm is around 0.085 dB/km. So, the average attenuation when the operating wavelength is 1.55 μm is only 39% of that obtained at 0.78 μm.

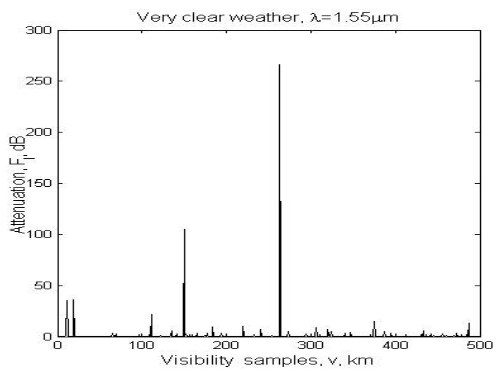

Fig. 3 Attenuation at λ=1.55 μm in very clear weather.

4.3. C1ear weather

One of weather conditions which a laser beam works in is the clear weather. In this weather, the visibility range is also considered in the high range, which can reach 18.1 km. Also, the medium particles concentration is low and hence, the absorbed power is low.

The effect of the visibility range, under the mentioned simulation parameters, on the atmospheric attenuation in clear weather for WOC is shown in Fig. 4. Despite the laser beam attenuation decreases when the visibility values increases, the laser beam of 1.55 μm wavelength experiences less attenuation than the other case of 0.78 μm. Moreover, results obtained in case of 0.78 μm show that the average attenuation is approximately twice that in case of 1.55 μm. Hence, one can predict the atmospheric attenuation of the optical ray through the clear weather condition to judge if the system will fit the purpose of use or not.

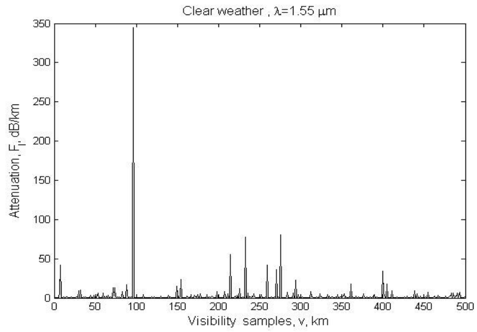

Fig. 4 Attenuation at λ=1.55μm in clear weather.

4.4 Light haze weather

In this section, we will investigate a less visibility range weather condition; light haze, where the visibility drops to 30% of the previously studied clear weather condition. The atmospheric attenuation for different visibilities is displayed in Fig. 5 for the wavelength 1.55μm.

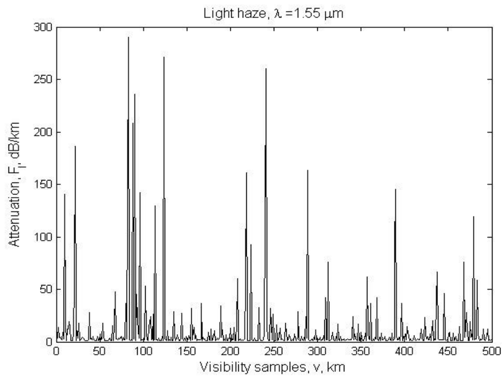

Fig. 5 Attenuation at λ=1.55μm in light haze.

It is clear that, the attenuation is greater than that occurred in the clear and the very clear weather. This is mainly due to the large drop of the visibility values. Compared to the operating wavelength 0.78μm, the average attenuation when the operating wavelength is 1.55 μm is less by about 45%.

4.5 Haze weather

In this weather condition, the visibility range is medium (2.8 km). According to (4), the average atmospheric attenuation is calculated and drawn with different visibilities at 0.78 and 1.55 μm as shown in Fig. 6. It is easily noted that the average atmospheric attenuation decreases with the visibility. The average attenuation in case of 0.78 μm is 5dB/km where, in case of 1.55 μm, it is 3 dB/km. Hence, the 1.55 μm is recommended in the design of WOC systems in the haze weather condition areas.

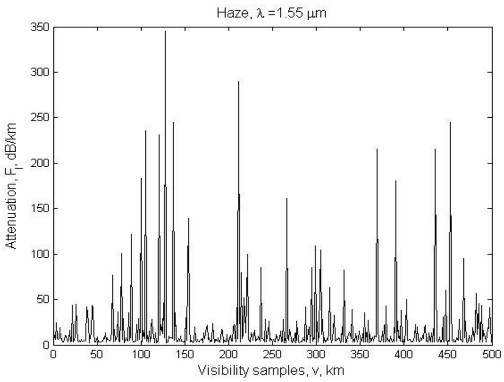

Fig. 6 Attenuation at λ=1.55 μm in haze weather.

4.6 Weather with thin fog

Now, the attenuation is investigated in weather with thin fog. The visibility range is decreased a little bit from the visibility range of the haze weather condition to be 1.9 km. This is carried out at 0.78, 1.3 and 1.55 μm, where the latter is shown in Fig. 7.

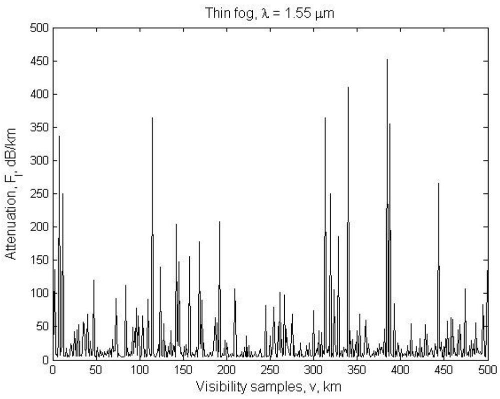

Fig. 7 Attenuation at λ=1.55 μm in thin fog.

In this case, the atmospheric attenuation at 0.78 μm increases by 50% of that obtained in case of haze weather condition. The average attenuation at 1.55 μm is approximately twice that of the haze weather conditions. This can be explained as follows: the particles density of the medium increase and so, the photons suffer more scattering and absorption and the mean free path decreases resulting in more attenuation. This increase in attenuation from haze weather condition to thin fog weather condition will affect the availability (will lower the availability) of the WOC system.

4.7 Weather with light fog

Light fog is a weather condition where the visibility starts to decrease dramatically to be in low visibility region, where it reaches 770 m. Therefore, more increase in the atmospheric attenuation is expected. The atmospheric attenuation is drawn against visibility in Fig. 8. The study for different wavelengths shows that at 1.55 μm, the atmospheric attenuation is less than that obtained at 0.78 μm by 45%. As expected, the attenuation at 0.78 μm and 1.55 μm in light fog weather condition is near three times of that of the thin fog weather condition at same wavelengths. Also, the attenuation at 0.78 and 1.55 μm in the thin fog weather condition is about fifteen times that of the very clear weather condition.

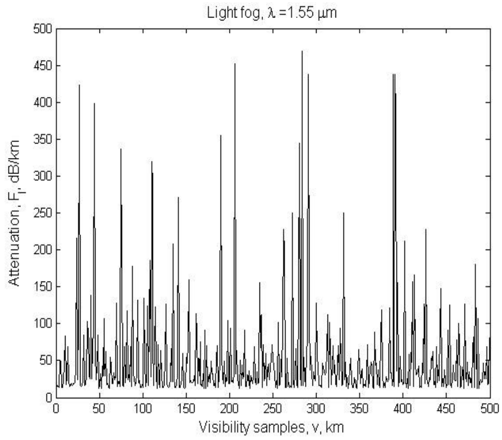

Fig. 8 Attenuation at λ=1.55 μm in light fog.

4.8 Weather with thick fog

In this section, the performance of outdoor WOC system, regarding to attenuation, is investigated in one of bad weather conditions which affects of the system availability; it is the thick fog condition, where the visibility drops to a very low value (≈ 200 m). As shown in Fig. 9, the attenuation is drawn with the visibility in the range of this weather condition for 1.55 μm operating wavelengths.

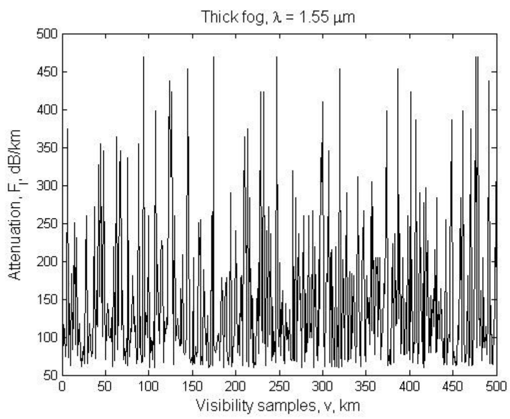

Fig. 9 Attenuation at λ=1.55 μm in thick fog.

The obtained results in this case shows that the attenuation increases dramatically compared to the other weather conditions. The attenuation at 0.78 μm operating wavelength is greater than that at 1.55 μm operating wavelength by 25%. As expected, the attenuation at 0.78 μm and 1.55 μm in the thick fog condition is, respectively, nearly four times and five times of the attenuation in light fog condition at the same wavelengths.

4.9 Weather with dense fog

Dense fog is the worst condition the system can face. The visibility decreases to the lowest value (≈ 50 m). Figure 10 displays the atmospheric attenuation in this condition for the operating wavelength 1.55 μm. In the dense fog condition, the particles concentration is very high and hence, the photons experience more scattering and absorption in their path from transmitter to receiver. Therefore, the attenuation is expected to increase compared to other weather conditions.

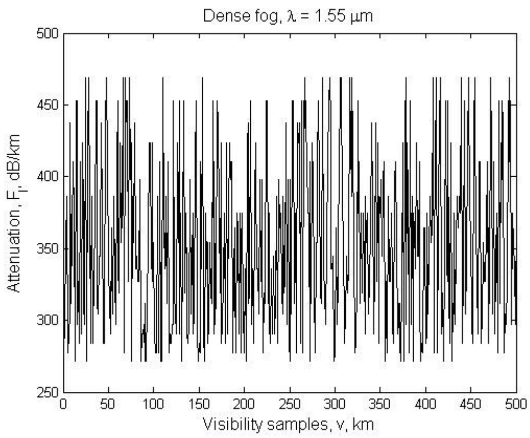

Fig. 10 Attenuation at λ=1.55 μm in dense fog.

Attenuation about 340 dB/km is obtained at the 0.78 μm operating wavelength which is greater by 20% than the corresponding one at 1.55 μm (about 275 dB/km). Like the thick fog condition, the atmospheric attenuation at 0.78 μm and 1.55 μm operating wavelengths in dense fog condition is, respectively, about four and five times of the attenuation in thick fog condition at the same wavelengths. It is obvious that the performance at 1.55 μm is better regarding the atmospheric attenuation which is less than that at 0.78 μm.

5. Conclusion

Atmospheric attenuation represents a critical factor in outdoor WOC. A quantitative study for atmospheric attenuation of a laser beam thought weather conditions for outdoor WOC system is carried out. The scope of the study was investigating the effect of weather condition on the laser beam. Atmospheric attenuation was calculated for different wavelengths in different weather conditions. The obtained results are summarized in Table 1.

Weather Condition	V(km)	Attenuation dB/km) at λ(μm) =		
		0.78	**1.3**	**1.55**
Very Clear	50	0.2	0.11	0.09
Clear	18.1	0.59	0.30	0.24
Light Haze	5.9	2	1.2	1
Haze	2.8	4.5	3	2.5
Thin Fog	1.9	7	6.1	4.2
Light Fog	0.77	18	14	12.5
Thick Fog	0.2	75	63	60
Dense Fog	0.05	320	284	275

Table 2 Atmospheric attenuation in different weather conditions.

The highest attenuation is obtained in the dense fog condition. In this condition, the 1.55 μm wavelength experiences less attenuation than the 1.3 and 0.78 μm wavelengths by 12% and 20%, respectively. Finally, the use of the 1.55 μm wavelength is recommended for low visibility range weather conditions.

6. References

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