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RESEARCH ARTICLE

Evaluation of light beams for short and medium range wireless communications

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Abstract Technological improvements in free space optical communication systems have reduced the cost and alternatives to fiber optic transmission. The advantages of the free space optical link over fiber optic cabling are primarily economic. In line with the demand for gigabyte link from 10 Mbit/s to 10 Gbit/s in the market, the uses of free space optical communication systems have increased exponentially from 1995 to 2008. However, free space optics is subject to atmospheric effects such as attenuation and scintillation which can reduce link availability and may introduce errors not seen in fiber transmission. In this paper we argue that optical wireless communication is an alternative to fiber optic transmission in short and medium range wireless communications and we discuss that the liability and availability of the free space optical link is mainly determined by the local atmospheric condition, this is to say that the transmission quality may be affected by weather conditions. For the evaluation we constructed an experimental communication network with a free space system. One way to characterize the strength of the turbulence fluctuation is by examining the Rytov variance for a plane wave. This Rytov variance physically represents the intensity fluctuation induced by atmospheric turbulence.

Keywords free space optical communication, atmospheric turbulence, scintillation

1 Introduction

Optical wireless communication (OWC) has become a more practical and high bandwidth access tool. Free space optical communication (FSO) is also called free space photonics (FSP). Optical wireless refers to the transmission of visible and infrared (IR) beams through the atmosphere. It is a line of sight optical technology in which voice, video, and data are sent through air on low power light beams at the speed of gigabytes per second.

The Federal Communications Commission (FCC) does not regulate frequencies above 300 GHz. Therefore, free space optical communications systems do not require an operating license. We have four types of free space optical communication systems: free space optical communication (satellite to satellite), free space to ground (terrestrial links), under water free space optics and terrestrial fiber less optical communication systems (atmospheric optical links).

Optical wireless is an alternative broadband solution (high bandwidth) for connecting the backbone to the users, and also acts as a local area network link between buildings. For space application, free space optical communication is potentially usable at interstellar distance. The application of fiber to the home (FTTH) is increasing exponentially as well as the need for connections between the fiber optic backbones to all types of businesses.

This technology provides a solution and networking capability which is not available in traditional telecommunication carriers, radio frequencies and microwave links. At the moment the main work in this type of technology is to increase reliability and availability. These two parameters of the free space optical link are mainly determined by the local atmospheric conditions. This paper is organized as follows: in Sect. 2, the atmospheric optical link is described; in Sect. 3, the fluctuations of the received optical signal are described; in Sect. 4, the experimental set up is explained; and in Sect. 5, experimental results and analysis are shown.

2 Light waves propagation in turbulent atmosphere

Wave propagation through random media like the atmosphere is often characterized by the structure constant (C_n^2)

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which is a measure of variance of the index of refraction n due to atmospheric turbulence [1]. The refractive index structure parameter C_n^2 m$^{2/3}$ is a parameter that is also used to describe the strength of atmospheric turbulence. C_n^2 can be approximately calculated as follows [2]:

$$\sigma_{\mathrm{Rytov}} = \sigma_i^2 = 1.23 C_n^2 K^{7/6} L^{11/6}, \tag{1}$$

where $K = 2\pi/\lambda$ is the optical number and λ (m) is the wavelength; L (m) is the propagation path length; $\sigma^2{}_i$ is the Rytov variance which represents the scintillation index or normalized irradiance variance.

The physical meaning of the refractive index structure function (c_n^2) is a measurement of strength of the fluctuations in the refractive index in the atmosphere. This parameter can be classified into two different regimes: weak turbulence and strong turbulence. Typically the values for weak turbulence regime are 10^{-17} m$^{-2/3}$ or less and for strong turbulence 10^{-13} m$^{-2/3}$ or more. The m$^{-2/3}$ units are derived from dimensional analysis. The Rytov method provides a solution for the variance of the log intensity fluctuations seen by point detector. The scintillation index is defined by

$$\sigma_i^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1, \tag{2}$$

where I is the intensity and the bracket $\langle \cdot \rangle$ denotes an ensemble average. Turbulent air motion represents a set of eddies of several scale sizes, where one is called the inner scale of turbulence and the other one is called the outer scale of turbulence. The inner scale of turbulence, outer scale of turbulence, and the structure parameter of the refractive index of fluctuation are the main parameters for characterization of turbulence in the atmosphere.

Weak turbulence regime:

$$\sigma_i^2 = 1.23 C_n^2 K^{7/6} L^{11/6} < 1;$$

Strong turbulence regime:

$$\sigma_i^2 = 1.23 C_n^2 K^{7/6} L^{11/6} > 1;$$

Saturation turbulence regime:

$$\sigma_i^2 \to \infty.$$

3 Light beam attenuation and weather condition

The only major disadvantage of the free space optical communication system is the effect of atmospheric turbulence on the light beam transmitted. These effects can be classified into two types: attenuation of light beam and fluctuation of light beam. This is due to light beam deformation [3]. The attenuation due to beam spreading can be calculated once the link distance is known, but the actual spreading is not considered attenuation. However, the light beam that is scattered out of the intended beam path is regarded as attenuation. Attenuation by the atmosphere is due to absorption and scattering by air, and the fluctuation of air is known as scintillation. Free space optics links are mainly affected by weather, especially fog and rain. The optical attenuation due to fog is generally more severe than that due to rain because the diameter of particles that compose fog are very close to that of the optical wave length, resulting in more scattering. To evaluate foggy conditions, visibility phenomena are usually used. The equation of the light beam transmission in air is described by Beer's law [3]:

$$\sigma \approx \beta_a = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q}, \tag{3}$$

where V is visibility in kilometers, λ is wave length in nanometers, and q is the size distribution of scattering particles:

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

Traditionally, the transmission losses between the source and receiver have been calculated using Beer's law [4,5]. It is common to choose a laser wavelength that makes the gas absorption and molecule scattering negligible. Aerosol absorption and molecule scattering are small compared with the aerosol scattering which dominates the total extinction coefficient. Atmospheric attenuation is

$$\tau(R) = \frac{P(R)}{P(0)} = e^{\sigma R}, \tag{5}$$

where $\tau(R)$ is transmittance at distance R, $P(R)$ is the laser power at distance R, $P(0)$ is the laser power at distance 0, and σ is the attenuation coefficient per unit length. The overall atmospheric attenuation coefficient is composed of four variables:

$$\sigma = \alpha_{\mathrm{m}} + \alpha_{\mathrm{a}} + \beta_{\mathrm{m}} + \beta_{\mathrm{a}}, \tag{6}$$

where α_{m} is the molecular absorption coefficient. Molecular absorption for free space laser data links have high absorption in the infrared band, which include absorption by water, ozone molecules and CO_2. α_{a} is the aerosol absorption coefficient. Aerosol absorption is a result of finely dispersed solid and liquid particles within the atmosphere such as ice, dust and organic particles, varying in size to a maximum of 4 μm in diameter. β_{m} is the

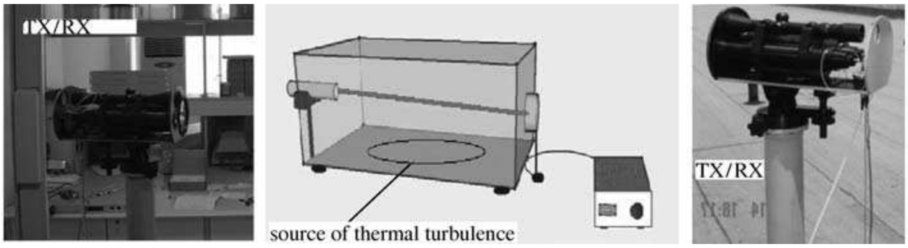

Fig. 1 Digital atmospheric optical link and laboratory thermal turbulence

molecular or Rayleigh scattering coefficient. Rayleigh scattering is a result of light interaction with particles which are much smaller than the propagating beam wavelength. The Rayleigh scattered power coefficient follows a λ^{-4} law and decreases with wavelength. β_a is the aerosol or Mie scattering coefficient. Mie scattering is the lower visibility condition, because haze, rain, snow and fog events are responsible for limiting free space optical ranges. The significant scattering attenuations occur only when the rates of rain and snow increase or there is an increase in fog densities.

4 Experimental set up

For modeling of thermal turbulence in a laboratory, we proposed to use an artificial atmospheric turbulence box. Several heaters can be used to produce thermal turbulences and the propagating beam moves above this thermal turbulence from transmitter to receiver. There are no included weather conditions like rainfall, fog or snowfall in this experimental model. Only the temperature turbulences can be observed. Figure 1 gives the digital atmospheric optical link and laboratory thermal turbulence.

5 Experimental results and analysis

In this basic model the refractive index structure parameter C_n^2 and the optical intensity variation σ_n^2 are calculated and optical intensity fluctuations are observed. The turbulence in the atmosphere can be characterized by three parameters: the inner scale, outer scale, and the structure parameter of refractive index fluctuations C_n^2. Figure 2 shows the characteristics of the strength of fluctuation index in atmosphere and the scintillation index that is caused by thermal turbulence. We calculated the value of C_n^2 by using Eq. (1). It is known that the scintillation index increases with an increasing value of C_n^2 until it reaches a maximum value in the regime characterized by being randomly focused [6]. The Rytov variance is also the function of distance, as shown in Fig. 3. From Fig. 3, we can see that the Rytov variance for typical C_n^2 values at propagation is up to 1 km, while Fig. 4 shows the fluctuation intensity of light when passing through the thermal turbulence. Figure 5 shows the influence of wavelength on visibility. It shows that different wavelengths have different attenuations.

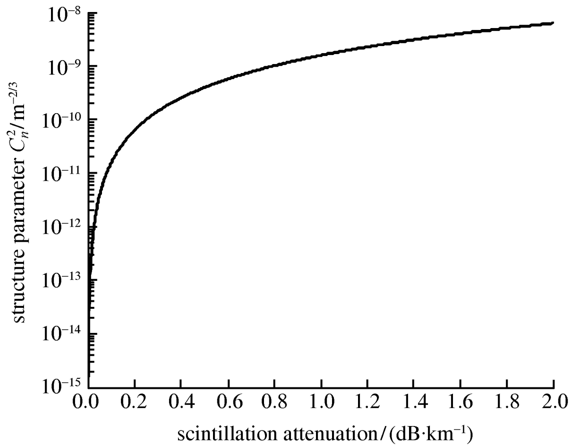

Fig. 2 Strength of fluctuation as a function of scintillation attenuation ($L = 2$ m, $\lambda = 632.8$ nm)

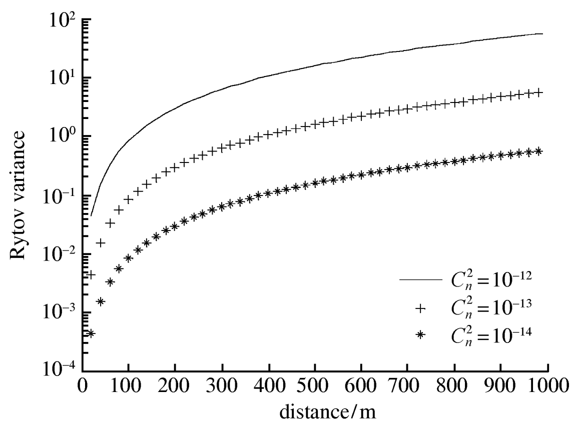

Fig. 3 Rytov variance at propagation distance ($\lambda = 632.8$ nm)

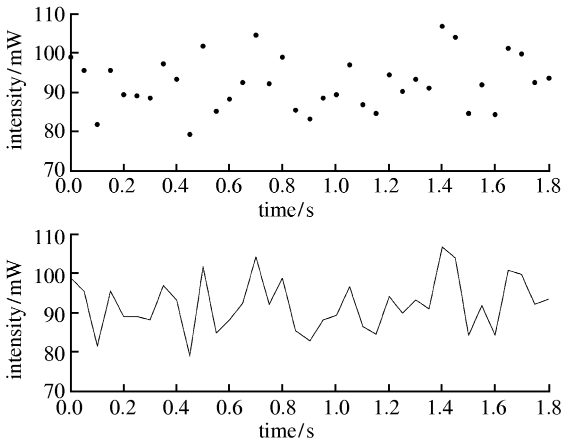

Fig. 4 Fluctuation intensity when light beam propagating through thermal turbulence

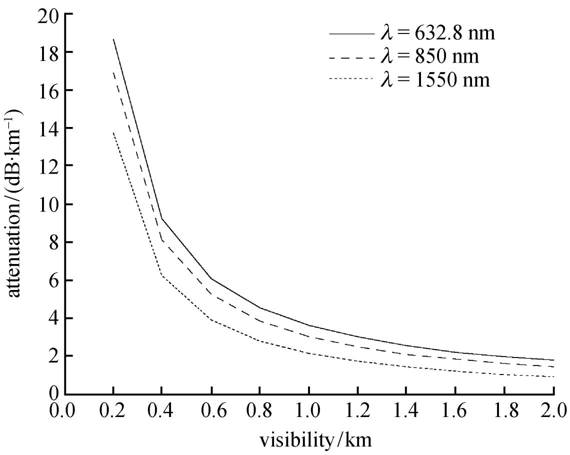

Fig. 5 Theoretical comparison of attenuation between wavelengths

6 Conclusions

Reliability and availability of free space communication is mainly determined by the local weather and not only by electrical and optical components and network infrastructure. The diminishing intensity of the propagation beam is caused by physical processes and increased distance from the source. This experiment gives enough information on the beam through a propagating thermal turbulence channel, and the results can be useful for estimating the strength of atmospheric turbulence. However, the free space optical link parameters are given by the manufacturer, but the determination of statistical parameters of the atmosphere is still problematic.

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