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Free-Space Optical communication using visible light

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Abstract: The possibility of visible red light laser being used as signal light source for Free-Space Optical (FSO) communication is proposed. Based on analysis of transmission in atmospheric channel concerning 650 nm laser beam, performance of wireless laser communication link utilizing a low power red laser diode was evaluated. The proposed system can achieve a maximum range of 300 m at data rate 100 Mb/s theoretically. An experimental short-range link at data rate 10 Mb/s covering 300 m has been implemented in our university. It is feasible to enhance the system performance such as link range and data rate by increasing transmitting power and decreasing laser beam divergence angle or through other approaches.

Key words: Visible light communication, Red light laser, Free-Space Optical communication, Wireless laser communication
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INTRODUCTION

A growing and seemingly insatiable bandwidth demand in the marketplace is bring Free-Space Optical (FSO) technology into the carrier space as a means of broadband access for closing the "last mile" connectivity gap throughout metropolitan networks. Terrestrial short-range FSO systems which are generally point-to-point links between buildings on the campus or different buildings of a company can be used to setup wireless communication networks or to supplement radio and optical fiber networks. Generally medium for short-range links is infrared radiation designed to operate in the windows of 780~850 and 1520~1600 nm (Leitgeb *et al*., 2003a) using resonant-cavity light emitting diodes and laser diodes.

This paper proposes a short-range FSO system using visible light ray (650 nm red laser beam) as the communication medium. Visible light communications comprise a technology for transmission of information using light that is visible to the human eye. The possibility is based on tremendous technical advances of available components at low cost and efficient modulation techniques. Pang *et al*.(1999a; 1999b; 2002) and Pang (2004) built a system made up of high brightness visible LEDs which reaches over 20 m outdoors and can provide the function of open space, wireless broadcasting of audio or data signal.

High power stable and continuous operation semiconductor LD at 650 nm has been developed for a long time, and is commonly used in optical access and storage system, laser printer or as indicators. A new feature of frequency modulation has been utilized as well due to their low cost and small size. In order to realize this system, study of atmospheric channel concerning red light laser ray is required. It is concluded through numerical analyses that visible laser beam can be used for terrestrial short-range FSO links. Performance parameters of the proposed system were evaluated in detail and experimental system was described finally.

COMMUNICATION LINK ANALYSIS

Atmospheric channel

FSO short-range applications can be used up to 1 km (up to 2 km) for connecting buildings or establishing a connection to the backbone. For short ranges, "auto tracking" is not necessary but it is important to know the influence of the path through the atmosphere. Atmospheric conditions affect system performance much and can be either simulated and modelled or measured over long time periods. The primary factors characterizing an atmospheric communication channel include ambient light, atmospheric attenuation (both scattering and absorption) and scintillation.

Ambient light that passes the optics and reaches the detector element generates additional current that leads to additional white Gaussian noise in the receiver. The dominant source of the ambient light for outdoor FSO systems is sun. Therefore the sunlight radiation and the possible positions of the sun have to be considered for practical applications. An intensity of about 1340 W/m^2 known as the solar constant, reaches the Earth and is reduced to about 1000 W/m^2 global radiation on the ground under clear sky conditions due to wavelength dependent absorption in the atmosphere. The specific sunlight radiation intensities are 0.5~0.9 W/(m^2·nm) in the 380~780 nm spectral regions with peak value in the 500 nm spectral region (Sidorovich, 2002). Generally, the impact of sunlight on FSO depends on the angular and spectral sensitivity of the receiver and the possibility of the direct sunlight at the receiver, regarding orientation and mounting of the installed system. Therefore terrestrial short-range links based on 650 nm wavelength laser beam which are usually horizontal can be well designed to alleviate the adverse effect of ambient light properly.

Attenuation of the optical wave (i.e., reduction of its power) by atmosphere can be caused in several ways (Leitgeb *et al*., 2003b), including absorption of light by gas molecules and Rayleigh or Mie scattering by gas molecules or aerosol particles suspended in the air. The atmospheric path for a laser beam concerning attenuation may be seen as an information channel on which information gets lost.

According to Beer-Lambert law, atmospheric transmission (Strohbehn, 1978) can be expressed by the extinction coefficient γ and the atmosphere path distance L:

$$\tau = P_{\mathrm{d}} / P_0 = \mathrm{e}^{-\gamma L}. \tag{1}$$

The transmission τ for an optical wavelength means the relation of the optical power P_{d} at the end of an atmospheric path of distance L to the optical power P_0 which was originally sent. The extinction coefficient γ is a result of absorption α and scattering β by particles in the atmosphere. In detail, these particles can be the molecules of the atmospheric gas constituents and the larger aerosol particles:

$$\begin{aligned}\gamma(\lambda) &= \alpha(\lambda) + \beta(\lambda) \\ &= \alpha_{\mathrm{m}}(\lambda) + \alpha_{\mathrm{a}}(\lambda) + \beta_{\mathrm{m}}(\lambda) + \beta_{\mathrm{a}}(\lambda).\end{aligned} \tag{2}$$

Absorption can be caused by water, oxygen, carbon dioxide and other gases of minor constituents in the atmosphere. Researches (Achour, 2002a; 2002b) showed that many wavelengths propagate poorly due to absorption by water vapor, particularly near 1300~1400 nm region. Absorption due to oxygen and carbon dioxide are only sensitive to some typical wavelengths except 650 nm.

Scattering from aerosols and particulates such as in fog, clouds, smoke and dust also contribute to the total attenuation of the optical beam. Interaction between laser waves and comparatively small particles can be simplified to Rayleigh scattering (Bohren and Huffman, 1983) and only get important for optical wavelengths smaller than 400 nm. However when both are approximately in the same order, which is most critical condition such as in haze or fog climate and the main important process that remains, scattering by aerosol particles is basically independent of wavelength and can be characterized by Mie theory (Van, 1991; McCartney, 1976).

It should be noted that the impact of rain (Achour, 2002a) is less critical because larger particle size in the order of 0.1 to about 5 mm diameter has more effect on longer wavelengths such as millimeter waves at several tens of GHz. Falling snow simply absorbs the light by the irregular shapes of particles in the size of about 2 up to 25 mm.

Attenuation coefficient (in dB/km) based on empirical measurement data was calculated by the following equation (Kim *et al*., 2000):

$$\gamma(\lambda) \cong \beta_{\mathrm{a}}(\lambda) \cong \frac{17.35}{V}\left(\frac{\lambda}{550}\right)^{-q}. \tag{3}$$

Visibility range V is the atmospheric path distance for a transmission of 2%. The parameter q in Eq.(3) depends on the visibility distance range and is given by the following equation (Kim *et al*., 2000; Sizun *et al*., 2002):

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

Fig.1 compares the transmitting attenuation coefficient of 650 nm, 850 nm and 1550 nm laser beam. It was found that the wavelength from visible light all the way up to infrared wave has almost no effect on propagation range under short-range conditions.

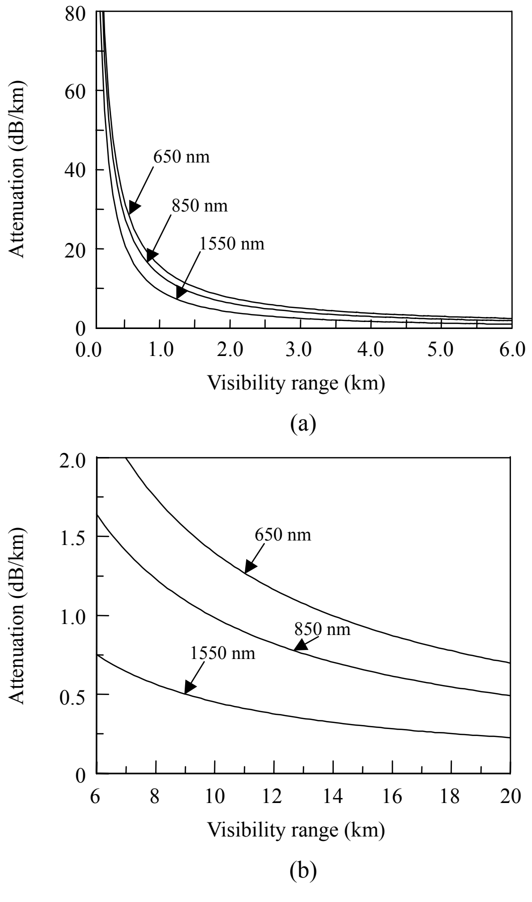

Fig.1 Comparison of attenuation among laser beams of different wavelengths. (a) Low visibility; (b) High visibility

Some typical values of terrestrial short-range path attenuations for 650-nm laser wave with corresponding visibilities are given in Table 1.

Table 1 Typical values of attenuation with corresponding visibilities

Climate	Visibility (km)	Attenuation (dB/km)
Clear	20.0	0.70
Haze	2.0	7.77
Thin fog	1.5	10.50
Light fog	1.0	15.96
Heavy fog	0.5	34.69

Scintillation is the fluctuation in the detector signal as a result of random variations in the refractive index n of the turbulent atmosphere along the channel. Influence of turbulence leads to irregular changing intensity in the beam, wave-front distortion and changing deviation of input power at the receiver. But it is not interesting for short-range FSO systems and can be ignored in the following calculation.

Light source and eye safety

The majority of Free-Space Optical communication systems were designed to operate in the infrared bands (780~850 nm and 1520~1600 nm) which already provided higher data rates and over longer distances (Ai *et al*., 2006). For short-range FSO system, using cheap light source which provides sufficient data rates in the range of tens of Mbps is a well suited solution. Low cost FSO systems using LEDs were developed by Leitgeb *et al*.(2002; 2003a) for data rates of 10 and 100 Mbps. For reliable, inexpensive, high-performance lasers around 650 nm are readily available, visible red laser instead of infrared ray was utilized here. Transmitter with visible light and receiver are easy to install and can provide high data rates without tracking system therefore have smaller size and cost less. Although visible light is appealing, eye safety is still a concern among laser communication systems. In terms of wavelength, the IEC60825 rulings permit longer wavelength devices to output much more power than shorter ones. The longer wave length system is thus readily designed to be eye safe. By the United States Center for Devices & Radiological Health (CDRH), visible laser light between 1.0 and 5.0 mW is considered eye-safe with caution if viewed for less than 0.25 s. Laser beam at 650 nm is supposed to be easily noticed by human eye while possible harm can be avoided promptly.

Performance evaluation

We shall consider in detail the situation of optical propagation between two points in terrestrial applications. Therefore received optical power, data rate, link margin and Signal-to-Noise Ratio (SNR) performance of a theoretically "perfect" short-range visible laser communications system are described below. A low power red light laser diode and a Si-PIN photodiode were employed with parameters given in Table 2 together with other parameters supposed in this simulation.

Table 2 System parameters in this "perfect" link analysis example

Parameter	Value
Laser wavelength (nm)	650
Transmitter optical power (mW)	5
Transmitter divergence angle (mrad)	1.0
Transmitter efficiency	0.5
Receiver sensitivity (dBm)	−20
Receiver diameter (cm)	10
Receiver efficiency	0.5
Detector field-of-view (mrad)	200

Consider a laser transmitting a total power $P_{\text{transmitter}}$ at the wavelength 650 nm. The signal power (Shaik, 1988) received at the communications detector can be expressed as

$$P_{\text{receiver}} = P_{\text{transmitter}} \frac{D^2}{\theta_{\text{div}}^2 L^2} 10^{-\gamma L/10} \tau_{\text{transmitter}} \tau_{\text{receiver}}, \quad (5)$$

where D is the receiver diameter, θ_{div} is the full transmitting divergence angle, γ is the atmospheric attenuation factor (dB/km), $\tau_{\text{transmitter}}$ and τ_{receiver} are the transmitter and receiver optical efficiency respectively. Received optical power versus link range is shown in Fig.2.

Link margin is defined as the ratio of available received power to the receiver power required to achieve a specified BER at a given data rate. The required power at the receiver P_{requried} is related by $P_{\text{requried}}=N_b Rhc/\lambda$. Combining the above equations yields the link margin expression (Shaik, 1988):

$$LM = [P_{\text{transmitter}} \lambda / (N_b Rhc)] \times [D^2/(\theta_{\text{div}}^2 L^2)] 10^{-\gamma L/10} \tau_{\text{transmitter}} \tau_{\text{receiver}}. \quad (6)$$

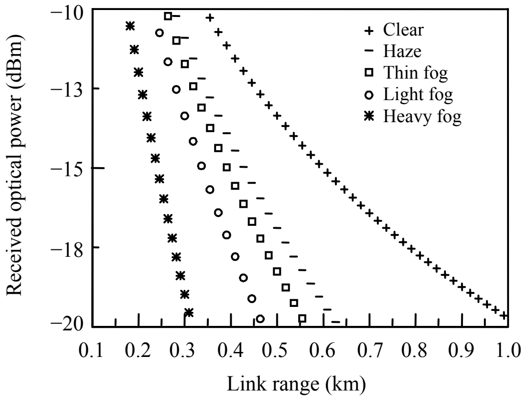

Fig.2 Received optical power versus link range

The link margin value shows how much margin a system has at a given range to compensate for scattering, absorption and scintillation losses. Fig.3 shows available link margin versus link range for the system (parameters given in Table 2) to achieve a given data rate 100 Mb/s operating under typical weather conditions. As seen in this figure, 13 dB of link margin is available for the proposed data link of less than 300 m.

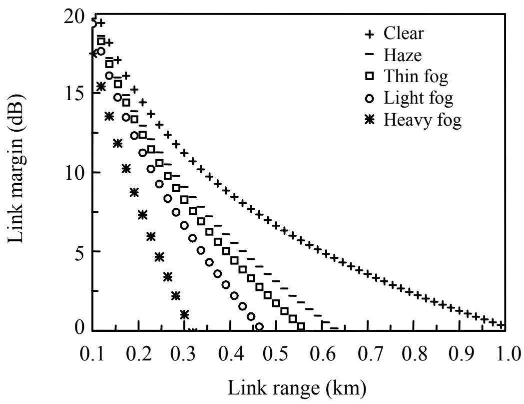

Fig.3 Link margin versus link range

Given the receiver sensitivity −20 dBm, which is equivalent to 327000 photons/bit at wavelength 650 nm, the achievable data rate (Majumdar, 2005) R can be obtained from

$$R = \frac{P_{\text{transmitter}} \tau_{\text{transmitter}} \tau_{\text{receiver}} 10^{-\gamma L/10} D^2}{\pi(\theta_{\text{div}}/2)^2 L^2 E_p N_b}, \quad (7)$$

where $E_p=hc/\lambda$ is the photon energy at wavelength λ and N_b is the receiver sensitivity (photons/bit). Data rate versus link range is shown in Fig.4. As can be seen, a maximum data rate of 100 Mb/s can be achieved for a range of 300 m under clear, haze and fog condition.

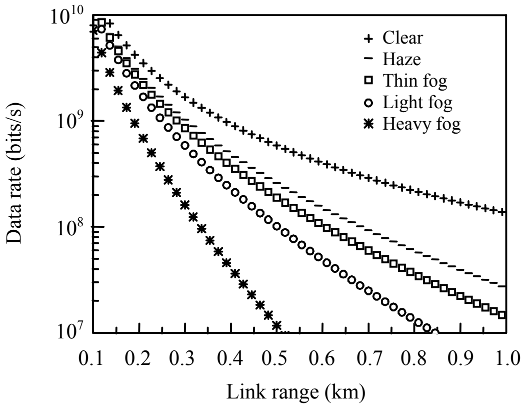

Fig.4 Data rate versus link range

To study the performance of the proposed visible light FSO system in realistic weather conditions, we performed calculations of the error probability associated with binary detection. If the data rate is to be 100 Mb/s, the SNR value of a high-bandwidth laser communication system as a function of one-way link range is shown in Fig.5. System parameters are the same as given in Table 2. We assumed the use of PIN/FET (Personick, 1973) receiver and background radiation power P_{bg}=0.01 mW. For a Bit-Error-Rate (BER) of 10^{-9} one needs average SNR of approximately 16.97 dB at the receiver. Fig.5 shows that the proposed system can achieve high SNR performance operating under various weather conditions. There are other parameters one can vary such as transmitter

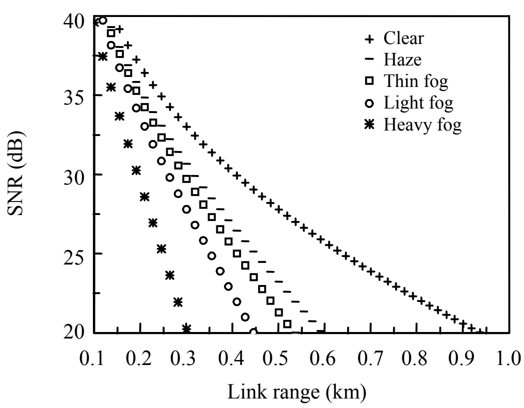

Fig.5 SNR versus link range

optical power, transmitter beam divergence and receiver diameter, etc. to change the SNR value for achieving a given data rate for longer application of the red light based FSO system.

Experimental descriptions

An experimental 300 m data link without tracking system has been implemented outdoors. Both the transmitter and receiver were mounted to different buildings (between science and technology building and a community). The transmitter laser source was a 5 mW LD at wavelength 650 nm operating at temperature of 25 °C. Output laser beam was collimated using a lens and transmitted pointing to remote receiver where laser was focused by a 10 cm diameter lens to the photo-PIN-diode. The receiver electronic structure includes photo-PIN-diode, amplifier and data-interface. An Si-PIN BPX photodiode, BPX-65 brand was utilized at the receiver. At 650 nm the receiver has a responsivity of 0.50 A/W. The data-interface converts the electrical signal into RJ-45 (10 Mb/s Ethernet). The transmission experiment was performed outdoors between short-range points so atmospheric scintillations can be ignored for the link investigated in this work. Installation of this FSO system is very easy because the laser beam can be easily captured by human eyes. A practical measurement was done over a period of spring time which showed that the performance of the system was very good. The major cause of unavailability was haze and fog because of Guangzhou's special weather, which mainly appears at the end of the day. Good reliability and availability can be achieved by using this system for short distances. Use of low-cost red light laser diode for short distances makes this link interesting for private users.

CONCLUSION

The 650 nm wavelength laser diodes were developed a long time ago and cost less. Atmospheric transmission of 650 nm laser beam was analyzed. Performance parameters of a short-range FSO system utilizing red light LD were calculated. We also describe our fundamental experiment based on a 650 nm wavelength laser diode.

As a medium for short-range FSO systems, 650 nm laser has both advantages and disadvantages when compared with infrared media. On the one hand, visible red laser sources capable of high-speed operation are available at low cost. Like the infrared, the visible spectral region is unregulated worldwide and FCC licenses are not necessary. On the other hand, it is suitable only for short-range communications, as the output power of red laser is restricted due to eye safety problem.

The following conclusions were made:

(1) Red light laser can be modulated and used as signal light source in carrier space communications;

(2) The proposed system using a 5 mW power LD can theoretically achieve a maximum range of 300 m at data rate 10 Mb/s and 100 Mb/s;

(3) Link performance can be optimized by varying system parameters such as transmitter optical power, transmitter beam divergence and receiver diameter, etc.

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