Performance analysis of free space optical communication system using homotopy perturbation method under different weather conditions

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Free Space Optics (FSO) is an optical communication technology where free space acts as a medium between the transceivers. In FSO as the light signal is transmitted through the atmosphere so it is essential to take weather conditions into consideration. In this paper, the performance of free space optics link is analyzed using homotopy perturbation method and investigated under different weather conditions by optimizing the beam divergence. In the designed system the optical source used is continuous wave (CW) laser with optical signal power of 40 mW. The signal with operating wavelength of 850 nm is transmitted in free space, experiences attenuation due to weather conditions such as rain, snow, fog. It is analysed that smaller beam divergence improves the performance of the system.

1. Introduction

In modern era of communication, there is need of a system with high channel capacity and bandwidth. Free Space optical technology (FSO) is a line of sight (LOS) communication which provides abundant advantages to both telecommunication users and providers [1,2]. For broadband communications the LOS technology transmits a modulated beam of visible or infrared light through the atmosphere. It provides a high data rates up to several Gbps, has immunity to radio frequency interferences and gives a highly secured communication link [3]. It can be taken as an ideal solution to last mile problem found in commercial applications. Due to wireless character of free space optics, it is an economical way of solving last mile problem [4]. FSO communication can be used in many optical links such as building-to-building, ship-to-ship, aircraft-to-ground [5]. In analysing the performance of FSO, it is essential to take several system parameters into consideration. These are divided into two categories internal and external. Internal parameters are related to design of a FSO system. It includes optical power, wavelength, beam divergence, optical loss on the transmitter side, receiver sensitivity and BER. External parameters are interrelated to the environment which includes visibility, atmospheric attenuation, scintillation, pointing loss. The quality and stability of FSO link is highly dependent on the atmospheric attenuation [6]. Attenuation is the reduction in the strength of the signal as it propagates through the medium as air in the case of free space optics.

2. Beam divergence analysis

One of the main advantages of FSO system is the ability to transmit narrow optical beam that can be achieved with well designed optics which enhances the security. This narrow beam allows for secure and efficient transmission with a major portion of the transmitted power being collected by the receiver. Beam divergence allows the beam to diverge or spread. In FSO the advantage of using narrow beam is to generate much higher data rates and to increase the security. The beam spread is dependent on the beam divergence angle and transmission range [7]. For a system with automatic pointing and tracking, the beam width can be narrowed significantly from 0.05 to 1.0 mrad of divergence and it is equivalent to a beam spread of 5 cm to 1 m at 1 km. By which link distance is improved and provide the system with greater link margin to conflict the weather conditions.
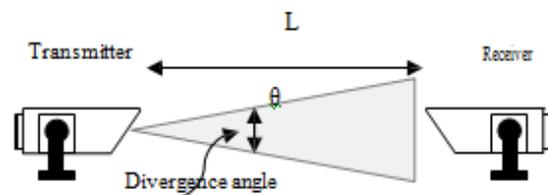
Fig. 1. The divergence angle between two FSO units [8]

The optical light beams exiting from transmitter are not perfectly collimated laser beam; they have a divergence angle as shown in Fig. 1. As a result, the light spreads out more as it get further away from the

transmitter terminal. The cross-section of the beam may be as much as several meters in diameter by the time it gets to the receiving terminal. The entire optical light beam actually does not hit the receiver aperture and much of it gets wasted around the sides of the terminal. By minimizing the beam divergence more light can be concentrated onto the opposite receiver aperture terminal. The commercially available FSO systems have a beam divergence of a few milli radians. Larger receiver aperture or smaller beam divergence results in less geometrical losses for a given range. Geometric path losses for a FSO link depends on the beam width of the optical transmitter, path length and aperture area and it is given by [8]

$$A_{geo} = 10 \log_{10}\left(\frac{\frac{\pi}{4}(R\emptyset)^2}{\pi r^2}\right) \qquad (1)$$

here R is the distance in km, $\emptyset$ is beam divergence in mrad and r is the radius of receiver aperture in meters.

3. Weather conditions

The atmospheric phenomenon affects the performance of wireless link when designing free space optics system. Some part of the transmitted signal lost in the channel due to atmospheric attenuation. The atmospheric condition not only attenuates the light wave but also distorts and bends it [9]. Attenuation is primarily the result of absorption and scattering by molecules and aerosols particles suspended in the atmosphere. In free space optics communication system, there are different weather conditions that affect the light propagation in free space. Therefore, atmospheric conditions can be a limiting factor in a reliable high data rate wireless free space optics communication link [10]. The performance of FSO is degraded by atmospheric conditions such as haze, fog, snow and rain etc.

3.1. Fog attenuation

Fog is composed of fine spherical water droplets of various sizes suspended in air. The size of water droplets are few hundred microns in diameter. It can modify the features of light and hinder the path of light. Fog consists of particles that stay longer in the atmosphere. The attenuation due to fog is given by Beer-Lambert's Law. According to Beer-Lambert's law the attenuation due to fog at distance R in the optical signal is given by [11]

$$A_{fog} = \frac{3.912}{V}\left(\frac{\lambda}{\lambda o}\right)^q \qquad (2)$$

where V is visibility in km, λ is wavelength of transmitting signals in nm, λ_o is visibility reference at wavelength in nm, q is size distribution coefficient of scattering. There are two models i.e. Kruse model and Kim's model for the calculation of particle size distribution coefficient q, in fog attenuation equation. The Kruse model define q factor as [12]

$$q = \begin{cases} 1.6 & \text{if } V > 50km \\ 1.3 & \text{if } 6km < V < km \\ 0.585V^{1/3} & \text{if } V < 0.5km \end{cases}$$

Kim modified Kruse model and define the size distribution coefficient q as

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

3.2. Snow Attenuation

Snow attenuation is classified as dry and wet. Dry snow is lesser dense and can be drifted easily by the wind but wet snow is more dense as compare to dry snow. Aerosol scattering effect caused by snow can also degrade the quality of free space optical communication system. The atmospheric attenuation due to snow is given by the relation [9]

$$\lambda_{snow} = \alpha S^b \qquad (3)$$

For dry snow, a = 5.42×10^{-5} + 5.49, b = 1.38,
For wet snow, a = 1.02×10^{-4} + 3.78, b = 0.72.
where S defines rate of snowfall in mm/hr and α, b are coefficients for dry and wet snow which is given according to International Telecommunication Union (ITU) recommendation.

3.3. Rain Attenuation

Other weather phenomenon affecting the propagation of an optical signal is the rain. The atmospheric rain absorbs and scatters the laser beam energy resulting in attenuation of the propagating signal [13]. Rain attenuation causes scattering of the beam when the beam passes through big size raindrops. The diameter of raindrops varies between 0.1 mm to 7 mm. Drops with diameter smaller than 2 mm are spherical. The smaller raindrops are cloud droplets where as larger raindrops are unstable have tendency to get fragmented. The rain particles stay shorter in the atmosphere so attenuation due to rain is less as compare to other atmospheric factors. The specific rain attenuation is described by the relation [14]

$$A_{rain} = kR^\alpha \qquad (4)$$

where R is rate of rainfall in mm/hr, k and α are power law parameters. The power law parameters depend on frequency, rain drop size distribution and rain temperature.

3.4. Scattering analysis using Homotopy Perturbation Method

The scattering coefficient (β) can be represented as a function of distance (d) between transmitter and receiver, i.e.

$$\beta\,(d) = \pi a^3 \beta'\,(d) + \frac{N Q_{scat}}{\lambda} \beta''\,(d) \qquad \text{with initial condition}$$

$$\beta\,(1) = 20 \text{ dB} \qquad (5)$$

where a is radius of raindrop, N is raindrop distribution, Q_{scat} is scattering efficiency, λ is wavelength, $\beta'\,(d)$ and $\beta''\,(d)$ are the first and second order derivative of scattering coefficient respectively. We can define Homotopy by

$$\pi a^3 \beta'\,(d) = P\Big(\beta\,(d) - \frac{N Q_{scat}}{\lambda} \beta''\,(d)\Big) \qquad (6)$$

Where He's homotopy perturbation method (HPM) considers the solution β (d) in a series of P as

$$\beta\,(d) = \sum_{k=0}^{\infty} P^k \beta_k \qquad (7)$$

Now,
$$\pi a^3 (\beta'_o + P\beta'_1 + P^2\beta'_2 + P^3\beta'_3 + ---) = P\Big[(\beta_o + P\beta_1 + P^2\beta_2 + P^3\beta_3 + ---) - \frac{N Q_{scat}}{\lambda}(\beta''_o + P\beta''_1 + P^2\beta''_2 + P^3\beta''_3 + ---)\Big] \qquad (8)$$

On comparing the coefficients of equal power of P,
$\beta_0 = 20$,
$\beta_1 = \frac{20d}{\pi a^3}$
$\beta_2 = \frac{20d^2}{2!(\pi a^3)^2}$
$\beta_3 = \frac{20d^3}{3!(\pi a^3)^3} - \frac{N Q_{scat}}{\lambda}\frac{20d}{(\pi a^3)^3}$
$\beta_4 = \frac{1}{(\pi a^3)^4}\Big[\frac{20d^4}{4!} - 20d^2 \frac{N Q_{scat}}{\lambda}\Big]$
$\beta_5 = \frac{1}{(\pi a^3)^5}\Big[\frac{20d^5}{5!} - \frac{20d^3}{3}\frac{N Q_{scat}}{\lambda} - \frac{20d^3}{6}\frac{N Q_{scat}}{\lambda} + 40d\frac{(N Q_{scat})^2}{\lambda^2}\Big]$
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Gives the solution as

$$\beta = 20 \exp\Big(\frac{d}{\pi a^3}\Big) - \frac{N Q_{scat}}{\lambda}\frac{20d}{(\pi a^3)^3}\Big[1 + \frac{d}{\pi a^3} + \frac{1}{2}\Big(\frac{d}{\pi a^3}\Big)^2 + \frac{1}{12}\Big(\frac{d}{\pi a^3}\Big)^3 + ----\Big] + \frac{40d}{(\pi a^3)^5}\frac{(N Q_{scat})^2}{\lambda^2}\Big[1 + \frac{3}{4}\Big(\frac{d}{\pi a^3}\Big) + ---\Big] \qquad (9)$$

Now, we can investigate the performance of the proposed system at different scattering coefficient with respect to d.

4. System design

The general block diagram of the free space optics communication under different atmospheric attenuation is shown in figure 2.
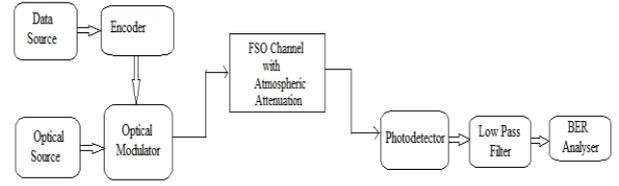
Fig. 2. FSO system with atmospheric attenuation

The light intensity of optical source is modulated linearly with respect to input electrical signal voltage. The optical source used is continuous wave (CW) laser with power of 40 mW. When signal is transmitted in free space at data rate of 1.25 Gbps, it experiences attenuation due to different weather conditions. The optical signal experiences attenuation due to moderate fog, heavy fog, rain and snow. At the receiving end, avalanche photodiode is used which responds to change in power level that directly falls on it using direct detection method. Direct detection technique used for an electro-optic conversion circuit employed in an optical communications system. The avalanche photo diode has a higher output current than PIN diode for a given value of optical input power. The photo detector transforms the optical power level variation back to original electrical signal format. The values of attenuation that is experienced by the optical signal when transmitted in free space channel for weather conditions such as rain, fog, heavy fog and snow is shown in table 1.

Table 1. Different weather conditions with attenuation

Condition	Attenuation
Rain	20 dB/km
Medium Fog	25 dB/km
Snow	46 dB/km
Heavy Fog	120 dB/km

5. Results and discussion
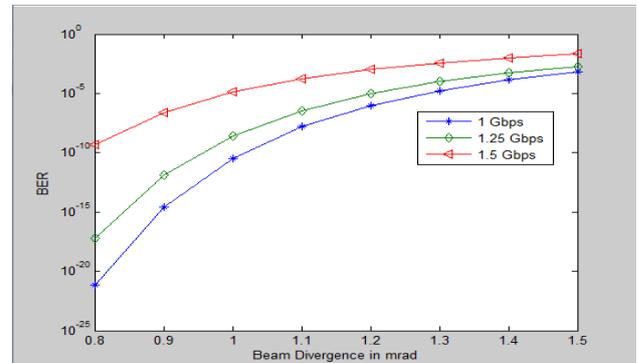
Fig. 3. Bit error rate versus beam divergence for FSO system

The performance of free space optics communication in terms of bit error rate at different values of beam divergence is shown in figure 3. The performance of system is analysed at attenuation 25 dB/km. It is observed that smaller beam divergence can improve the performance of system. For smallest value of beam divergence BER of 7.42×10^{-22} is obtained and beam divergence of 1.5 mrad gives BER of 6.18×10^{-4}. There is spreading of beam as it emerges out from transmitter terminal therefore narrow beam allows a secure communication link. Hence smaller beam divergence gives satisfactory link performance.
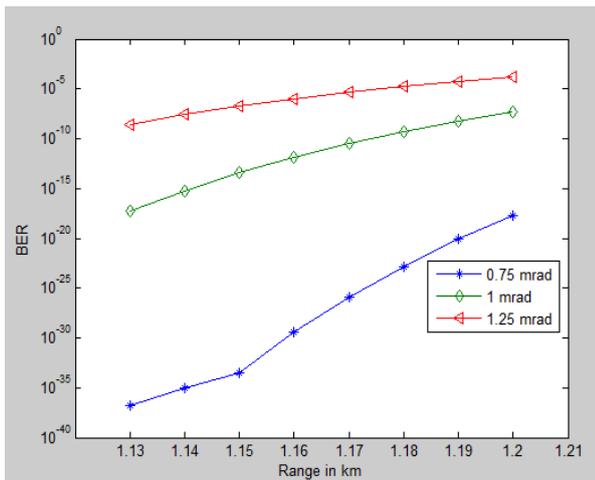
Fig. 4. Bit error rate versus range for moderate fog (25dB/km) at 1 Gbps

Variation of BER versus link range for moderate fog is shown in figure 4 and figure 5 at data rate of 1 Gbps and 1.25 Gbps respectively. The system gives better results at lower data rate as compare to higher data rate. Scattering and absorption due to atmospheric factors like fog and rain cause beam spreading and link distance reduction. For moderate fog condition beam divergence of 0.75 mrad gives BER for a given range as compare to beam divergence of 1.25 mrad with attenuation 25dB/km.
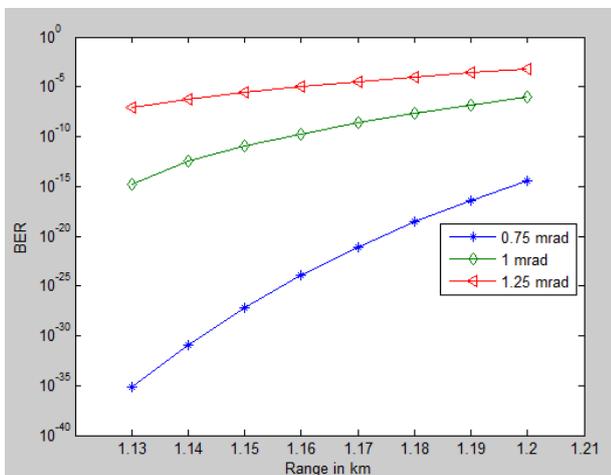
Fig. 5. Bit error rate versus range for moderate fog (25 dB/km) at 1.25 Gbps
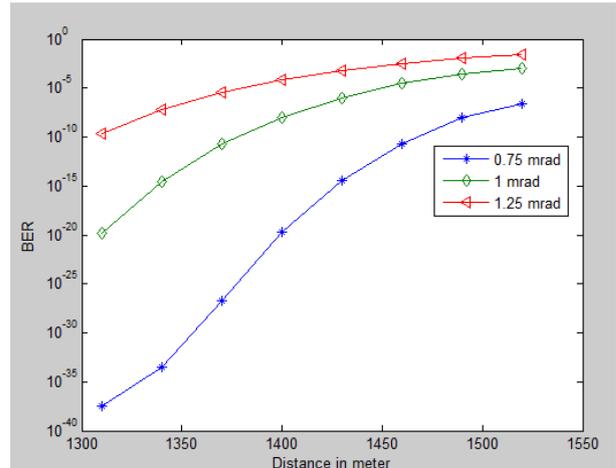
Fig. 6. Bit error rate versus distance for rain at 20 dB/km attenuation

The result of distance versus BER with different beam divergence for rain and snow is shown figure 6 and figure 7. Attenuation in rain is less than fog and snow therefore an optical signal can travel more distance. It is analyzed from the figure with increase in link distance; the performance of system degrades, as attenuation increases. But by optimizing the beam divergence the system performance can improve. The optical signal with attenuation 20 dB/km have minimum BER of 2.18×10^{-7} at beam divergence of 0.75 mrad but BER 2.46×10^{-2} is observed at beam divergence 1.25 mrad. Figure 7 shows distance vs. BER diagram for FSO system at attenuation of 46 dB/km. The distance is varied from 700 m to 770 m. It has been analysed BER reduces from 6.73×10^{-14} to 6.96×10^{-4} in the transmission range 700 m to 770 m at 1 mrad and if beam divergence increases to 1.25 mrad BER varies from 1.59×10^{-7} to 1.68×10^{-2} which degrade system performance.
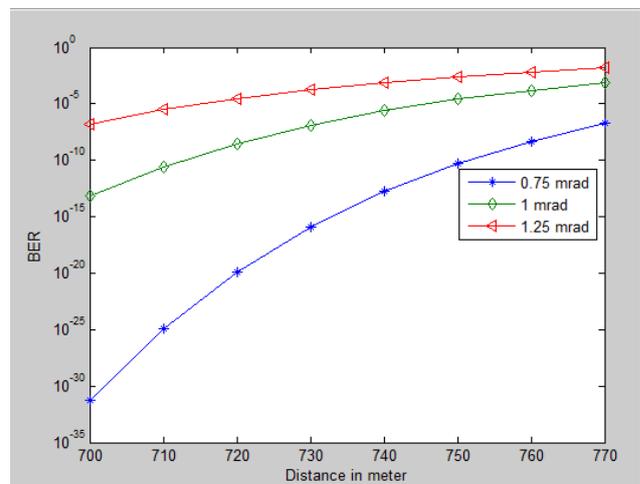
Fig. 7. Bit error rate versus distance for snow at 46 dB/km attenuation

6. Conclusion

In this paper, the performance of 1.25 Gbps free space optics communication system is investigated with different weather conditions. It is observed that rain and snow particle provides less attenuation to optical beam. But attenuation due to fog is more as compare to rain and snow because fog is composed of water droplets with radii about the size of near infrared wavelength. Thus transmission range becomes less due to increase in attenuation. From the results it is clear that transmission range decreases as move from rain to fog attenuation but by using small beam divergence the performance of system can be improved. It is analysed from the result a large beam divergence corresponds to poor beam quality.

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