Performance analysis of optical wireless link under various atmospheric conditions using Fresnel lens technique

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In an optical wireless link the atmospheric effect has a major impact on the performance of optical beam transmission in different weather environment. This investigation based on different weather circumstances such as clear, haze, thin fog, light fog and heavy fog on data rate, received signal and signal to noise ratio at 1550 nm wavelength for a free space optical communication. It is possible to enhance the system performance such as data rate, received power and S/N ratio in different weather condition by Fresnel lens technique. By using this technique, non coherent light source such as LED has been used instead of LASER in free space optical communication. The potential of LEDs to be modulated at high speeds offers the possibility of using LED as sources for communication instead of LASER. Simulation results shows that in all weather conditions, the performance of the system improved by using Fresnel lens technique and heavy fog attenuates more optical signal then other atmospheric condition.

(Received October 29, 2014; accepted March 19, 2015)

Keywords: Optical wireless, Fresnel lens, LED, Atmospheric effect

1. Introduction

The free space optical communication systems have various advantages over radio frequency (RF) communication systems such as larger bandwidth, high gain and smaller antenna size [1, 2]. The Free Space Optics has widely used in many applications, such as space communications, ad-hoc network installations, aircraft-to-aircraft communications, satellite communication, military applications and the last-mile solutions [3–8].

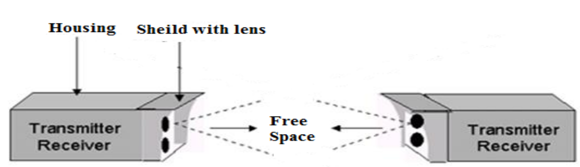

Fig. 1: Free space optical communication link

Apart from this there are various challenges faced by optical wireless system. Due turbulent environment, a laser beam experiences indiscriminate refractive index fluctuations along its path. The indiscriminate refractive index fluctuations cause random wavefront distortion, beam wander, and beam broadening [9–16]. All these propagating effects result in average received power loss and power received fluctuation called fading on the receiver side. Both fading and power loss causes decreased data rate and Signal to noise ratio.

Previous studies on optical wireless have been emphasized on the effect of attenuation due to the atmosphere such as rain, haze and fog [17-20]. Atmospheric effects are different for different system for example radio-relay system, microwave system, laser beam system etc. [21].

As far as free space optical communication has a concern, fog is the key factor for degradation of optical signal, especially for visible and IR waves [22, 23].

So the performance of optical wireless has been considerably degraded and limited due to scattering and absorption phenomenon due to fog particles of the environment. Fog and snow are the most undesirable weather conditions for FSO as they imply a high reduction in optical wave [24]. Numerous work and models on atmospheric visibilities and connected optical attenuation has been published previously [25-27].

Different approaches have been implemented to diminish the power loss and fading troubles like multiple aperture transmitter and receiver [28–30], adaptive optics technique [31, 32].

This work study the performance of free space optical communication system in different weather conditions using the Fresnel lens technique for LED beams with 1550 nm wavelength under the heavy fog, light fog, thin fog, haze, and clear conditions.

2. Fresnel lens for free space optical communication

Fresnel lens has low cost and light weight lens available in large sizes so that provide an opportunity to use in free space optical communications. They are used for collimating beams of light and focusing light from a far source into an optical detector [33].

Fresnel lens are not perfect enough to attain the diffraction limit, so it cannot be used to properly collimate a coherent light source like laser and hence attempt to do so can cause in a considerable portion of the light being scattered. That is why non-coherent light source like LED can also be used instead of LASER in free space optical communication. In optics, the f-number (sometimes called focal ratio) of an optical system is the ratio of the lens's focal length to the diameter of the entrance pupil. It is a dimensionless number.In optical system, Fresnel lenses are designed that have a F-number in the between 0.5 to 1.5. It is also feasible to use a Fresnel lens as a collimator in optical system to produce highly-parallel beams similar to spotlight as seen in diagram 2. [33]

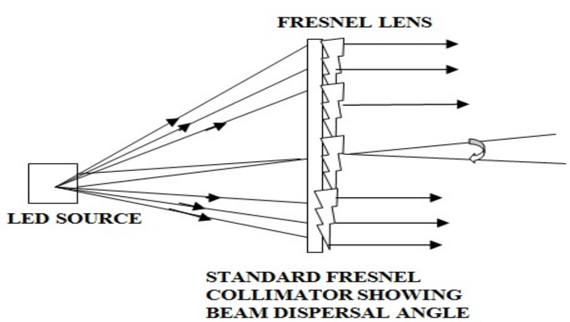

Fig. 2. Fresnel lens used to collimate light from an LED.

Sometimes, a secondary lens can be placed very close to the LED to reduce the angle over which the LED light has been cast to allow a much greater proportion of it to arrive at the lens. [33]

3. Signal power at the receiver

Consider a super luminescent LED that transmits a power P_t at the 1550 nm wavelength. The detector received a power that has evaluated as follows [34]

$$P_{r1} = P_t \frac{D^2}{\theta_{div}^2 L^2} 10^{-\gamma L/10} \tau_t \tau_r \quad (1)$$

Where 'D' represents the diameter of receiver aperture, 'θ' is divergence angle, 'γ' is the attenuation factor (dB/m). Transmitter and receiver optical efficiency represented by $\tau_{t,}$ and τ_r respectively.

By introducing the lens at the transmitter side, the total power becomes

$$P_{ttotal} = P_t + 10 \log_{10} N_t \quad (2)$$

Where N_t represent the number of transmitter lenses of a single FSO unit

At the detector of receiver, the new equation of power after the introduction of lens technique as follows

$$P_{r2} = P_{ttotal} \frac{D^2}{\theta_{div}^2 L^2} 10^{-\gamma L/10} \tau_t \tau_r \quad (3)$$

4. Data Rate

The achievable data rate R_1 for transmitter power P_t with divergence θ, receiver aperture diameter D and transmitter, receiver efficiency τ_t, τ_r can be evaluated as [35]

$$R_1 = \frac{P_t \tau_t \tau_r 10^{-\gamma L/10} D^2}{\pi(\theta/2)^2 L^2 E_p N_b} \quad (4)$$

Here, $E_p = hC/\lambda$, has the photon energy.

Now by introducing lens technique, the newly expression represented as

$$R_2 = \frac{P_{ttotal} \tau_t \tau_r 10^{-\gamma L/10} D^2}{\pi(\theta/2)^2 L^2 E_p N_b} \quad (5)$$

5. Signal to noise ratio

The received optical signal has electrical power which is proportional to mean squared current of avalanche photodiode APD [36]

$$\langle i_{APD}^2 \rangle = (R_0 P_{r1} M)^2 \quad (6)$$

and,

$$R_0 = \frac{\eta q \lambda}{hC} \quad (7)$$

Where R_0 represent sensitivity, M represents gain, η denotes efficiency of APD, q denotes charge on the electron.

Shot noise has major concern as far as Signal to Noise ratio calculation is concern. Shot noise exists because phenomena such as light consist of the movement of discrete 'packets', coming out of a laser at random times, this cause the relative fluctuations in number of photons, These fluctuations are shot noise.

If average signal current is much larger, then dark current can be ignored. This corresponds to high optical power and small dark current. If the shot-noise power by far exceeds the thermal-noise power, then the thermal power can be ignored.

The expression for shot noise

$$\sigma_{\text{shot noise}}^2 = 2q(R_0 P_{r1}) M^{x+2} B \quad (8)$$

The expression for surface leakage current

$$\sigma_{\text{surface}}^2 = 2q I_L B \quad (9)$$

The multiplied dark current noise

$$\sigma_{dark}^2 = 2q(I_D)M^{x+2}B \quad (10)$$

The Johnson noise

$$\sigma_{Johnson}^2 = \frac{4KTBF_T}{R_{eq}} \quad (11)$$

The excess noise factor

$$F(M) = M^x(0 \leq x \leq 1) \quad (12)$$

Where I_D represents bulk dark current, I_L represent surface leakage current, k denotes Boltzmann constant, B denotes noise equivalent bandwidth, Req represents circuit equivalent resistance, F_T represents noise figure of the electric circuit and T is the temperature of system and x is a parameter whose value ranges from 0.3 to 0.5 for silicon APDs and 0.7 to 1 for germanium APDs.

The SNR for the optical wireless system then evaluated as [36]

$$SNR_{APD} = \frac{(R_0P_{r1}M)^2}{2q(R_0P_{r1}+I_D)M^{x+2}B+2qI_L B+4KTBF_T/R_{eq}} \quad (13)$$

Now by introducing lens technique, the newly expression of SNR

$$SNR_{APD} = \frac{(R_0P_{r2}M)^2}{2q(R_0P_{r2}+I_D)M^{x+2}B+2qI_L B+4KTBF_T/R_{eq}} \quad (14)$$

6. Simulation Results

The results, based on the equation model analysis and the set of the working parameters are shown in table (1) [37].

Table 1: System parameters used in this simulation for 1550 nm

Parameter	Value
Wavelength	1550 nm
Transmitter Optical Power (mw)	100
Transmitter Efficiency	0.5
Transmitter Divergence Angle(mrad)	1≤θ≤3
Efficiency of Receiver	0.5
Sensitivity of Receiver (dBm)	-20
Diameter of Receiver (cm)	1≤D≤10
Range (meter)	1≤L≤1000
Dark Bulk Current(I_D)	0.05 nA
Gain of APD	100
Excess Noise Fator(x)	0.5
Electrical Band(B)	25 MHz
Leakage Surface Current(I_L)	0.001 A
Temperature of system(T)	290 K
Noise Figure factor(F_T)	3 dB
Equivalent noise Resistance(R_{equ})	50 kΩ

Table 2: Atmospheric attenuation in (dB/km) as a function of visibilities for 1550 nm [38]

Climate	Visibility (km)	Attenuation (dB/km)
Clear	23	0.49
Haze	2	6.50
Thing Fog	1.5	8.98
Light Fog	1	13.95
Heavy Fog	0.5	34.70

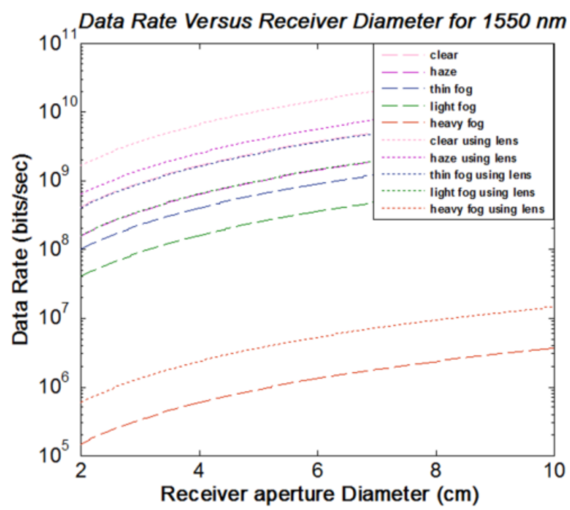

Fig. 3: Data rate versus receiver diameter for 1550 nm

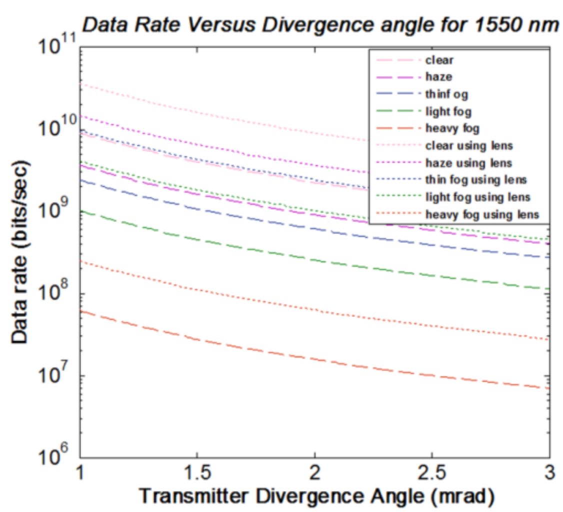

Fig. 4: Data rate versus divergence angle for 1550 nm

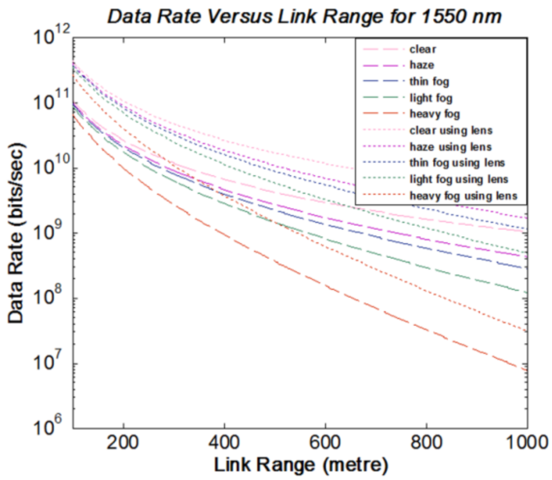

Fig. 5: Data rate versus link range for 1550 nm

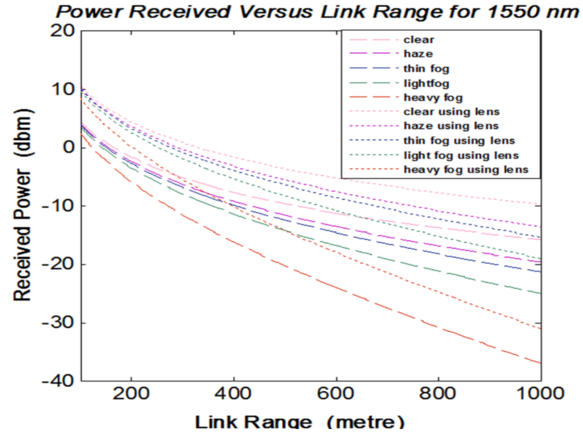

Fig. 8: Power received versus link range for 1550 nm

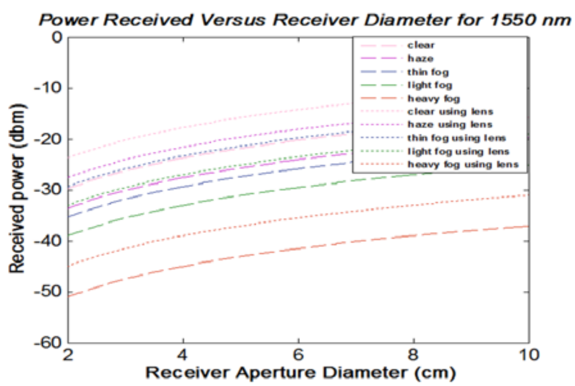

Fig. 6: Power received versus receiver diameter for 1550 nm

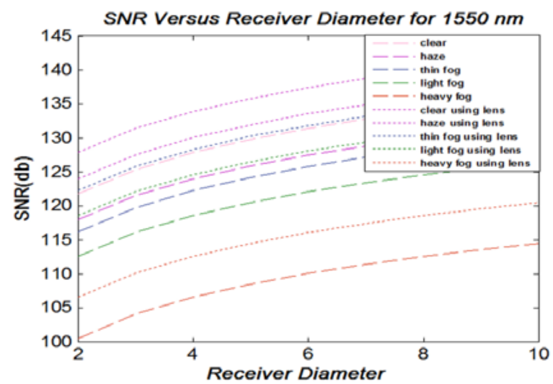

Fig. 9: SNR versus receiver diameter for 1550 nm

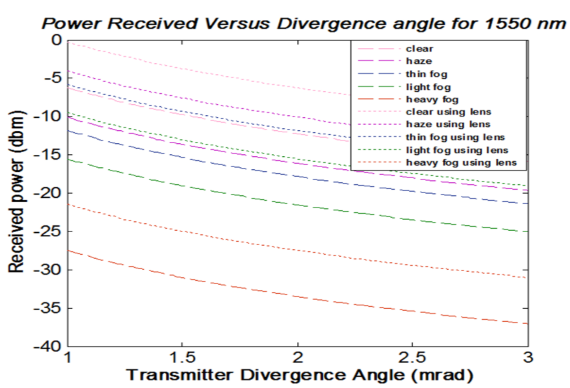

Fig. 7. Power received versus divergence angle for 1550 nm

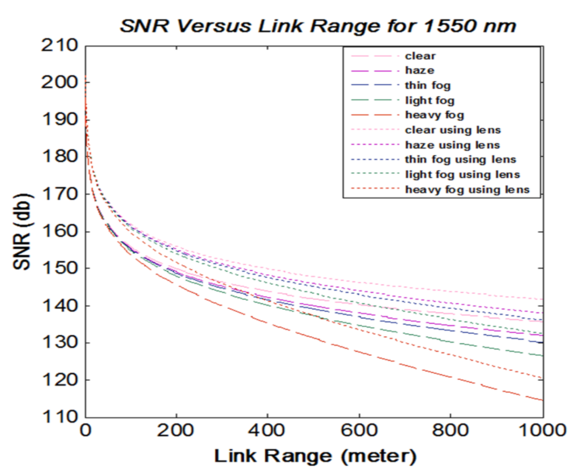

Fig. 10: SNR versus link range for 1550 nm

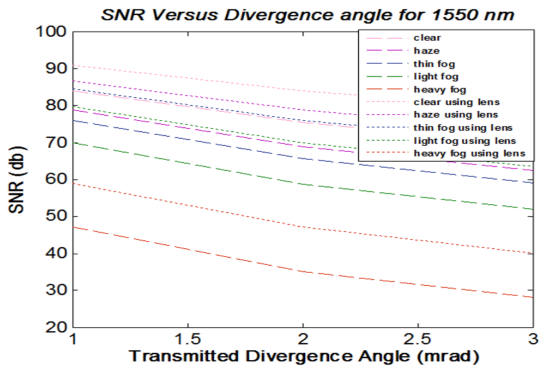

Fig. 11: SNR versus divergence angle for 1550 nm

7. Result Summary

Investigation of free space optical communication system in different weather condition by using a Fresnel lens technique offer high quality results and performance which has shown in all simulation figures. Table 3, Table 4 and Table 5 shows improvement in various parameters in heavy fog condition, as heavy fog degrade optical signal severely.

Table 3: Improvement in power received and S/N ratio at diffrent link range

Wave-length (nm)	Link Range (meter)	Atmospheric Condition	Lens Technique	Power Received (dbm)	Improvement (%)	S/N Ratio (dB)	Improvement(%)
1550	100	Heavy Fog	With lens	11.83	104	16.33	4
			Without lens	5.81		15.73	
	500	Heavy Fog	With lens	-10.72	36	14.08	5
			Without lens	-16.74		13.48	
	1000	Heavy Fog	With lens	-27.46	18	12.40	5
			Without lens	-33.48		11.80	

Table 4: Improvement in power received and S/N ratio at different Transmitter divergence (Tx)

Wave-length (nm)	Tx Divergence (mrad)	Atmospheric Condition	Lens Technique	Power Received (dbm)	Improvement (%)	S/N Ratio (dB)	Improvement (%)
1550	1	Heavy Fog	With lens	-21.44	22	5.88	25
			Without lens	-27.4		4.70	
	1.5	Heavy Fog	With lens	-24.97	19	5.20	30
			Without lens	-30.99		4.01	
	3	Heavy Fog	With lens	-30.99	16	4.01	43
			Without lens	-37.01		2.80	

Table 5: Improvement in power received and S/N ratio at different receiver diameter (Rx)

Wave-length (nm)	Rx Diameter (cm)	Atmospheric Condition	Lens Technique	Power Received (dbm)	Improvement (%)	S/N Ratio (dB)	Improvement (%)
1550	4	Heavy Fog	With lens	-41.44	12.6	11.00	5.76
			Without lens	-47.46		10.40	
	6	Heavy Fog	With lens	-31.90	15.8	11.96	5.28
			Without lens	-37.92		11.36	
	10	Heavy Fog	With lens	-27.46	17.9	12.40	5.08
			Without lens	-33.48		11.80	

From the results shown in figure 3, 4 and 5, the data rate of more than 10 Gb/s has achieved for diverse parameters under different atmospheric conditions at 1550 nm. The data rate goes down with a rising transmitter divergence angle and range, while it increases with an increase in diameter of the receiver for the conditions under study. It has been observed that results in all weather conditions are improved by using lens technique. The received signal power in different weather condition like heavy fog, light fog, thin fog, haze and clear has been shown for receiver aperture diameter, transmitter divergence angle, link range at 1550 nm in figs.6,7 and 8.

It can be inferred that received signal power increases with increasing receiver diameter and decreases with increasing transmitter divergence angle and range for the condition under work. It has been shown that results in all weather condition are improved by using lens technique.

The simulation results are shown in Figs. 9, 10 and 11 to observe the signal to noise characteristics in different atmospheric conditions. When the diameter of receiver increases, then signal to noise ratio increases for the system under consideration. Results indicate that heavy fog attenuates more optical signal than the other weather conditions.

8. Conclusion

This study focused on the atmospheric effect on optical beam in free space optical communication at 1550 nm. This analysis is based on data rate, received signal and signal to noise ratio in heavy fog, thin fog, light fog, haze and clear condition. Effect of receiver aperture diameter, transmitter divergence angle and link range on the received signal, data rate and signal to noise ratio has been shown in the simulation results. Simulation results shows that received signal, data rate and signal to noise ratio decreases with transmitter divergence angle, link range and these parameters increases with receiver aperture diameter. Fog has severe effect on the optical link as it attenuates more optical signal, this can be seen in the Tables 3,4 and 5. By the introduction of Fresnel lens technique, non coherent light source like LED are also utilized instead of LASER in free space optical communication. For this technique, the performance of free space optical communication has been improved and data rate of more than 10 Gb/s has been achieved.

Now a days, demand of FSO deployment increases for civil applications, but the provision of long range FSO links covering several kilometers with 99.999% availability in all weather condition especially in fog remains a difficult task, so more research will require to mitigate atmospheric turbulence in free space optical communication.

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