Performance Analysis of FSO Communication System: Effects of Fog, Rain and Humidity

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***Abstract*—Free Space Optics (FSO) is one of the most promising new access technologies. FSO provides the transmission of data with unlimited bandwidth. The atmospheric attenuation is caused by two main factors absorption and scattering. This paper investigates a performance study of free space optics channel for variable wavelengths 850 nm, 950 nm and 1550 nm at distance range of 1 km. The simulation reports minimum BER for NRZ-OOK modulation technique at different receiver diameters in presence of fog, rain and humidity attenuation. The obtained results reflect the system improvement achieving minimum BER and maximum received power that can be detected at distance 1 km.**

Keywords—free space optics (FSO); fog; rain; humidity.

I. INTRODUCTION

FSO communication, also termed as optical wireless, is an optical communication technology that uses line of sight communication system and tries to achieve the need for high bandwidth over short distances [1]. There are various atmospheric attenuation effects on FSO link such as fog, rain, snow, humidity and temperature [2]. The majority of FSO systems are using 850 nm, 950 nm and 1550 nm [3-5] wavelengths. Research studies have shown that fog is the most important factor because the size of fog particles is comparable to the transmission wavelength of optical and near infrared wave [6].

This paper proposes model for the attenuation due to fog, rain, humidity and temperature using NRZ-OOK simulation technique and study the link performance using different wavelengths to enhance the system performance aiming to achieve minimum BER and maximum received power, link margin and data rate at transmission distance 1 km by choosing the suitable wavelength and receiver diameter. Performance parameters of the proposed system were evaluated in detail. The paper has been organized as follows: after introduction in section I, the fog, rain and humidity and temperature attenuation model is considered in section II. The performance evaluation of FSO system described in section III. The simulation results are performed in section IV to show the effect of the attenuation on FSO system and conclusions are drawn in section V.

II. ATTENUATION MODEL FOR FSO

The interaction between the laser beam and air molecules and aerosols along the propagation produces the atmospheric attenuation. The beam power has an exponential decay relation with the propagation distance.

The transmittance for an optical wavelength is the relation of the transmitted power P_t and the received power P_r of an atmospheric link distance L. According to Beer-Lambert law as shown in (1) the optical transmittance τ is [7,8]:

$$\tau(\lambda, L) = \tau_s + \tau_a = \frac{P_r}{P_t} = e^{-\gamma_T . L} \quad (1)$$

where γ_T the overall attenuation coefficient, resulting from four individual processes (molecular and aerosol absorption coefficients in addition to molecular and aerosol scattering coefficients), τ_s is the scattering transmittance and τ_a is the absorptive transmittance [9].

A. Fog Attenuation

The two main scattering mechanisms are the Rayleigh scattering and the Mie scattering. The Rayleigh scattering occurs when the wavelength of the light is bigger than the particle size, and the Mie scattering occurs when the particle size is comparable to the wavelength of the radiation [8]. The fog is the major photon scatterer because its particle size compares very much with the wavelength band of interest in FSO (0.5 μm – 2 μm), this make Mie scattering the dominant scattering process in FSO systems. The scattering transmittance is given by (2) [8]:

$$\tau_s = e^{-\gamma_{fog} . L} \quad (2)$$

where γ_{fog} the attenuation due to fog is given by (3) [7] :

$$\gamma_{fog}(\lambda) = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-\delta} \quad (3)$$

here, V stands for visibility in km, λ stands for wavelength in nm and the parameter δ is visibility dependence. From (3), it is clear that for any weather conditions, the wavelength is inversely proportional with the attenuation. For Kruse model δ is given by (4) [10].

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$$\delta = \begin{cases} 1.6 & V>50km \\ 1.3 & 6km < V < 50km \\ 0.58\, V^{1/3} & V<6km \end{cases} \quad (4)$$

Kim model is wavelength independent for low visibility in dense fog. The value of δ for Kim model is given by (5) [10]:

$$\delta = \begin{cases} 1.6 & V>50km \\ 1.3 & 6km < V < 50km \\ 0.16V+0.34 & 1km < V < 6km \\ V-0.5 & 0.5km < V < 1km \\ 0 & V<0.5km \end{cases} \quad (5)$$

Al Naboulsi has provided relations to predict fog attenuation. It describes advection and radiation fog separately for wavelengths from 690 to 1550 nm [11]. The advection fog is created by the movements of wet and warm air masses above the colder maritime and terrestrial surfaces. Al Naboulsi provides the advection fog attenuation coefficients as:

$$\gamma_{Advection}(\lambda) = \frac{0.11478\lambda + 3.8367}{V} \quad (6)$$

Radiation fog is related to the ground cooling by radiation. Al Naboulsi provides the radiation fog attenuation coefficients as:

$$\gamma_{Radiation}(\lambda) = \frac{0.18126\lambda^2 + 0.13709\lambda + 3.7502}{V} \quad (7)$$

The specific attenuation for both types of fog is given by Al Naboulsi as follow

$$\alpha_{spec} = \frac{10}{\ln(10)}\gamma(\lambda) \quad (8)$$

B. Rain Attenuation

Rainfall increases the scattering coefficient. The transmittance of rain can be given by [8]:

$$\tau_{rain} = e^{-\gamma_{rain} \cdot L} \quad (9)$$

where γ_{rain} is the rain specific attenuation in (dB/km) and it is given by (10) [12]:

$$\gamma_{rain} = a\, R_{rain}{}^{b} \quad (10)$$

where R_{rain} the rainfall rate in mm/hr, a and b are power law parameters which depend on frequency, raindrop size, rain temperature and polarization. In calculating the rain attenuation it is sufficient to assume that raindrops have spherical shape which makes a and b independent of polarization. There are two models to calculate a and b, Marshal and Carbonneau models [13].

Carbonneau's model is used as the acceptable because Simulation found that the rain attenuation affect for marshal model less than for Carbonneau model because in marshal model an empirical expression based on fitting data is used, while Carbonneau used a physical method based on measurements data. a and b for Carbonneau model equal to 1.076 and 0.67 respectively [13].

C. Humidity Attenuation

The molecular absorption results from water, CO_2 and ozone molecules. The aerosol absorption results from the finely dispersed solid and liquid particles in the atmosphere. To calculate absorption, assumes that variations in the transmission are caused by changes in the water content of the atmosphere. The precipitable water, ω (in millimeters) is given by (11) [8]:

$$\omega = 10^3 . \rho . l \quad (11)$$

where ρ is the absolute humidity in (g/m^3). This value can be related with the water vapour pressure P_w and with the temperature T in degrees Celsius illustrated in (12) [8]:

$$\rho = 2.16679\, . P_w / T \quad (12)$$

where the water vapour pressure P_w is given by (13) [8]:

$$P_w = A\, . 10^{\left(\frac{m \times T}{T+T_n}\right)} . RH/100\,\% \quad (13)$$

where RH is relative humidity percentage, A, m and Tn are constants equal to 6.116441, 7.591386 and 240.7263 respectively.

The absorptive transmittance is given by [8]:

$$\begin{aligned} \tau_a &= e^{(-A_i * \omega^{1/2})} & \omega < \omega_i \\ \tau_a &= k_i (\frac{\omega_i}{\omega})^{\beta_i} & \omega > \omega_i \end{aligned} \quad (14)$$

The typical values of the constants A_i, k_i, β_i and ω_i are equal to 0.0305, 0.8, 0.112 and 54 respectively for 850 nm wavelength, and 0.0363, 0.765, 0.134 and 54 respectively for 950 nm wavelength and for 1550 nm are equal to 0.211, 0.802, 0.111 and 1.1 respectively. The total attenuation is the sum of the several partial attenuation factors.

III. Performance Evaluation of FSO System

The receiver optical power, link margin, data rate and bit error rate BER are considered to evaluate the performance of FSO system.

A. Received optical power for FSO

For a FSO communication link, the received signal power P_r is given by (15) [14]:

$$P_r = P_t \frac{D^2}{\theta_{div}^2 L^2} 10^{-\gamma L/10} \tau_{trans} \tau_{rec} \quad (15)$$

where P_t is the transmitted power, L is the link distance, D is the receiver diameter, θ_{div} is the full divergence angle, γ is the total attenuation factor (dB/km) and τ_{trans} and τ_{rec} are the transmitter and receiver optical efficiency respectively.

B. Link Margin for FSO

Link Margin is defined as the ratio of available received power to the received power required to achieve a specified BER at a given data rate. The required power is given by [14]:

$$P_{Req} = N_b R h c / \lambda \quad (16)$$

Equation (17) shows the link margin LM [14]:

$$LM = P_t(\lambda/N_bRhc)\,\frac{D^2}{\theta_{div}^2L^2}10^{-\gamma L/10}\tau_{trans}\tau_{rec} \qquad (17)$$

where N_b is the receiver sensitivity (photons/bits) or (dBm), R is a data rate, h is a plank constant and c is the light velocity.The link margin value shows how much margin a system has at a given range to compensate for scattering and absorption losses [14].

C. The Achievable Data Rate

Given a laser transmitter power P_t , with transmitter divergence of θ_{div}, receiver diameter D, transmit and receive optical efficiency τ_{trans} and τ_{rec} , the achievable data rate R can be obtained from (18) [14]:

$$R = \frac{4}{\pi E_p N_b}P_r \qquad (18)$$

where $E_p = hc/\lambda$ is the photon energy at wavelength λ and N_b is the receiver sensitivity (photons/bit).

A. Signal to Noise Ratio and Bit Error Rate

For the performance of FSO system the SNR and BER is considered. For the PIN photodiode the signal to noise ratio (SNR) is given by (19) [9]:

$$SNR = \frac{I_P^2}{2qB(I_P + I_D) + 4KT_{PIN}BF_n/R_L} \qquad (19)$$

where I_P is the average photocurrent, q is the charge of an electron (C), Brepresents the bandwidth, I_D is the dark current, T_{PIN} is the absolute photodiode temperature (K), F_n is the photodiode figure noise equal to 1 for PIN photodiode, R_L is the PIN load resistor.

The average photocurrent I_P can be expressed as (20) [9]:

$$I_P = P_rR_{PIN} \qquad (20)$$

where P_r is the average optical power received to the photodetector, R_{PIN} is the responsivity of the photodetector.

Another feature of FSO communication systems is the bit error rate BER. However, OOK modulation technique is mostly used in FSO communication systems. BER for NRZ-OOK modulated signal is given by [9]:

$$BER_{NRZ-OOK} = \frac{1}{2}erfc\left(\frac{1}{2\sqrt{2}}\sqrt{SNR}\right) \qquad (21)$$

IV. Simulation Results

Simulation is carried out to show the effect of fog, rain and humidity on FSO system when applying NRZ-OOK modulation technique in the transmitter and PIN photodiode is used in the receiver. Kruse model is chosen in simulation due to its wavelength dependency [6], while the values of the temperature, relative humidity and rainfall rate are the average values in Alexandria, Egypt in the last year. The performance of FSO system can be evaluated by the received optical power, link margin, achievable data rate and BER of the system. The values of the simulation parameters are given in Table I.

Fig. 1 shows the relation between the received signal power and the link distance using 850 nm, 950 nm and 1550 nm wavelengths at receiver diameter (D) equal to 15 cm.

The received signal power and the distance have inverse relationship because that when the signal reached to a long distance transmission, it faces more atmospheric particles which causes more scattering and absorption attenuation. It is also observed that the three wavelengths curves have closer behavior for low distances but different behavior for distance larger than 0.3 km for all receiver diameters. For receiver diameter 5 cm, the transmission distance is limited to 0.7 km. When the diameter increases also increase the transmission distance, it allows distance limits increases to 0.93 km for 10 cm diameter. When the receiver diameter 15cm is used, 850 nm and 950 nm wavelengths distances reached to 0.93 km and 0.95 km, respectively. But for 1550 nm capable for a longer distance reached to 1.06 km.

TABLE I. OPERATING PARAMETERS OF FSO SYSTEM

Operating Parameter	Value
Transmitter Power (P_t)	5 mW
Laser Beam Divergence Angle (θ_{div})	1 mrad
Transmitter Efficiency (τ_t)	0.9
Receiver Efficiency (τ_r)	0.9
Wavelength (λ)	850, 950 and 1550 nm
Range (L)	$0.1 \leq L \leq 1$ km
Visibility (V)	1 km
Average Atmosphere Temperature (T)	20 ^{0}C
Average Atmosphere Relative Humidity (RH)	67.9 %
Rain Rate (R_{rain})	18.3 mm/hr
Receiver Sensitivity (N_b)	-20 dBm
Data Rate (R)	100 Mb/s
PIN Load Resistance (R_L)	1 kΩ
Boltzmann Constant (K)	1.38×10^{-23} J·K
Absolute Photodiode Temperature (T_{PIN})	298 K
Dark Current (I_D)	10 nA
Responsivity (R_{PIN})	0.6 A/W
Electrical Bandwidth (B)	0.5 GHz

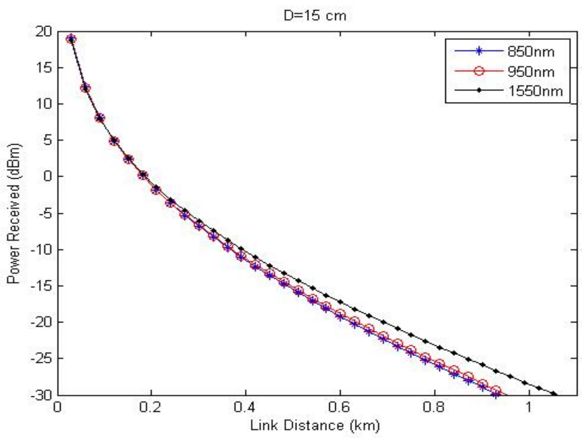

Fig.1 Receiver signal power versus distance under different wavelengths.

The achievable data rate versus link distance at D = 15 cm is shown in Fig. 3. A data rate 100 Mb/s can be achieved for a distance less than 0.9 km when applying the three wavelengths 850 nm, 950 nm and 1550 nm. By increasing the receiver diameter the data rate is increased. It is also observed that 1550 nm gives the higher data rate in all cases of receiver diameter.

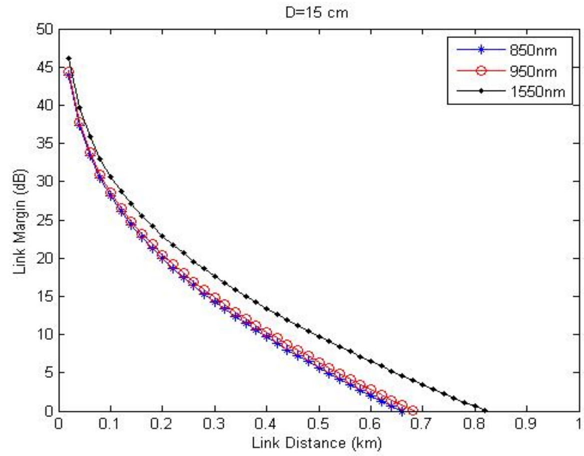

Fig. 2. Link margin versus distance under different wavelengths.

BER is considered to evaluate the performance of FSO communication system. Fig. 4, illustrates the BER performance as a function of distance. It shows BER for NRZ-OOK modulation under different wavelengths at D = 15 cm. When a 5cm receiver diameter is used, it is observed that the BER is 10^{-10} at a distance ~ 0.56 km at 850 nm and 950 nm.

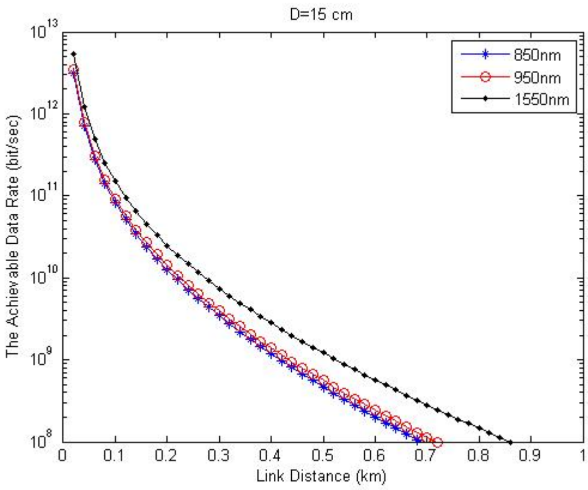

Fig. 3. Data rate versus distance under different wavelengths.

The distance could be increased to 0.6 km at 1550 nm, when a 10 cm receiver diameter is used. When 1550 nm wavelength is applied the distance is increasing about 0.8 km while for 850 nm & 950 nm the distance is about 0.73 km and 0.75 km respectively. An improvement in the transmission distance can be achieved by using a receiver diameter 15 cm. It is observed that the maximum data transmission is increasing for 1550 nm wavelength. It reached to 0.95 km, while reaching to 0.84 km and 0.86 km for 850nm and 950nm, respectively.

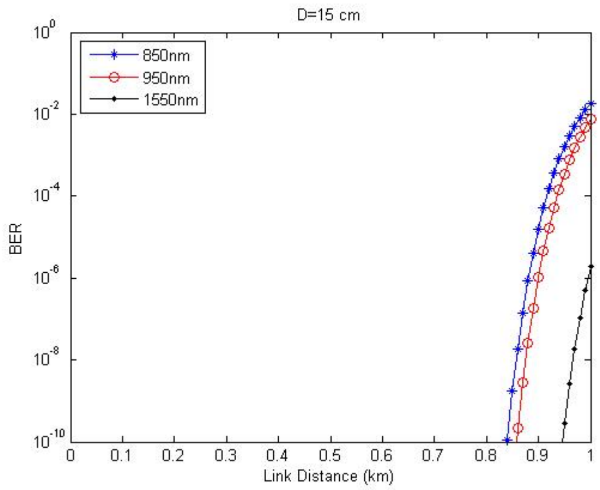

Fig. 4. BER versus distance under different wavelengths.

V. Conclusion

This paper presents a theoretical analysis for the attenuation in an FSO communication channel due to fog, rain and humidity. The performance is studied using NRZ-OOK modulation technique in the transmitter and a PIN photodiode in the receiver at three different wavelengths. The specific attenuation coefficient of the laser beam due to fog has a significant effect on the performance of FSO communication systems. Furthermore, the results show that both Kim and Kruse models could work under longer distances than that of AL Naboulsi model. It is observed that Kim and AL Naboulsi models are wavelength independent, on the contrary Kruse model. The receiver signal power, link margin, data rate and BER are investigated to evaluate the performance of the system. Selecting a suitable wavelength has a strong impact on the attenuation coefficient, which leads to longer transmission distances. Increasing distance causes a decreasing in received signal power, link margin and data rate and BER. The obtained results show that the 1550 nm has the greater advantages than the other wavelengths. It also shown that increasing the receiver diameter from 5 cm to 15 cm leads to an increase in the transmission distance to more than 1 km, the transmission distance of the link margin is enhanced by 61% and the transmission distance of the data rate is enhanced by 63%. The system can achieve 10^{-10} and 10^{-6} BER at distance 0.95 and 1 km, respectively, for a receiver diameter of 15 cm at wavelength 1550 nm. The simulation results show that attenuation due to both humidity and rain attenuation is added to fog attenuation resulting in an increase in the total weather attenuation. This requires choosing suitable wavelengths and suitable receiver diameters to achieve minimum BER and a detectable received power at the PIN receiver at distance 1 km.

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