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FSO Communication Characteristics under Fog Weather Condition

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Abstract: In this paper, the performance of an FSO wireless communications system is theoretically analyzed, using NRZ-OOK and 16-PPM modulation formats and a Si PIN photodiodes receiver over fog weather conditions. Four fog models are used for optical beam propagation horizontally at different wavelengths, the visibility of weather and received signal power is analyzed. The characteristics of bit error rate BER for NRZ -OOK and 16-PPM optical modulation formats are studied. Simulation results indicate that the performance of 1550nm is more suited for an FSO communication system. On the other hand, we discuss the suitability of fog models under these modulation formats.

Keywords: fog attenuation, BER, visibility, free space optics, modulation.

I. Introduction

FSO communication is gaining acceptance these days owing to low power and mass requirements, high data rate and unlicensed spectrum. FSO communication systems use laser diode or LEDs to produce a signal in near infrared range, i.e., they are operating at 780-900nm and 1500-1600nm [1].

Light travels through air faster than glass, so FSO is communication at the speed of light in atmosphere. The stability and quantity of the link is highly dependent on atmospheric factors such as rain, fog, dust and heat. The quality of the transmission is characteristics by the realized bit error rate [2]. Simplest form of FSO links are on-off keying (OOK) modulated links which involve presence and absence of optical pulse for binary '1' and binary 'o' respectively. Besides ease of modulation and development, following features have made unbeatable option in comparison to conventional RF systems, (i) FSO links use unlicensed IR frequency spectrum (ii) immunity to electromagnetic interference (iii) huge bandwidth and data rates as high as 10 Gbps (iv) FSO links are plug and play devices independent of transmission protocol (v) high end user privacy due to infrared based on line of sight (LOS) [3]. The transmission of modulated light is greatly affected by the atmospheric parameters such as absorption, scattering, and non-selective scattering. Absorption is caused due to gases present in the atmosphere, whereas scattering and non-selective scattering is caused by big sized rain drops. In temperature regions, fog and heavy snow are the primary weather conditions that affect FSO link [4]. The channel characterization in real atmospheric fog is accomplished by using the empirical approach [5-7]. The empirical approach uses the measured visibility and fog attenuation to evaluate the link performance. The visibility is normally measured using a visibility device called the transmissometer. However, it is sometime difficult to accurately measure the visibility and therefore the corresponding fog attenuation because of inhomogeneous for along FSO path. In addition measurement equipment and systems required are complex and very costly [8].

II. Attenuation by Fog

For a terrestrial FSO link transmitting optical signal through the atmosphere, the received signal power at a distance, L from the transmitter signal power for FSO is given by

$$p_r = P_t \tau_t \tau_r \frac{D^2}{\theta^2 . L^2} 10^{-\gamma(\lambda).L/10} \qquad (1)$$

Where D is the receiver diameter, θ is the full divergence angle; γ is the atmospheric attenuation factor (dB/km), τ_r and τ_t are the receiver and transmitter optical efficiency respectively.

The function of $\gamma(\lambda)$ is the total extinction coefficient per unit length, which represents the attenuation of the transmitted light. It is composed of terms for scattering and absorption, and general it is the sum of the following terms [11]

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$$\gamma(\lambda) = \alpha_m(\lambda) + \alpha_a(\lambda) + \beta_m(\lambda) + \beta_a(\lambda) \quad (2)$$

The first two terms represent the molecular and aerosol absorption coefficients, respectively while the last two terms are the molecular and aerosol scattering coefficients respectively. The wavelengths used in FSO are basically chosen to coincide with the atmospheric transmission windows [12, 13], resulting in the attenuation coefficient being dominated by scattering the attenuation is reduce to:

$$\gamma_{specific}(\lambda) \cong \beta_a(\lambda) \quad (3)$$

Attenuation coefficient based on empirical measurement data was calculated by the following empirical model [14]

$$\beta_a(\lambda) = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-\delta} \quad (4)$$

Where V is the visibility in (km), λ represent the wavelength in (nm). The parameter δ depends on the visibility distance range, according to Kruse model δ is given as [15]

$$\delta = \begin{cases} 1.6, & if\ V \succ 50km \\ 1.3, & if\ \ 6km \succ V \succ 50km \\ 0.585.V^{1/3}, & if\ V \prec 6km \end{cases} \quad (5)$$

While Kim model defines δ as [13]:

$$\delta = \begin{cases} 1.6, & if\ V \succ 50km \\ 1.3, & if\ \ 6km \succ V \succ 50km \\ 0.16V + 0.34, & if\ 0.5\,km \prec V \prec 6km \\ V - 0.5, & if\ 0.5\,km \prec V \prec 1km \\ 0, & if\ \ V \prec 0.5km \end{cases} \quad (6)$$

Al-Naboulsi proposed expressions to predict the wavelength dependent fog attenuation coefficient for the convection and advection fogs for wavelengths from 690 to 1550 nm [16]. The attenuation coefficient for convection fog is given by:

$$\gamma_\lambda(con) = \frac{0.11478\,\lambda + 3.8367}{V(km)} \quad (7)$$

The attenuation coefficient for advection fog is given by:

$$\gamma_\lambda(adv) = \frac{0.18126.\lambda^2 + 0.13709 + 3.7205}{V(km)} \quad (8)$$

The specific attenuation coefficient for both types of fog is given by

$$\gamma_{specific}(\lambda)\left(\frac{dB}{km}\right) = \frac{10}{\ln(10)}\gamma(\lambda) \quad (9)$$

III. Signal to Noise Ratio& Bit Error Rate

The main features of an FSO communication system is the signal to noise ratio SNR. When transmitted optical signals arrive at the receiver, they are converted to electronic signals by photo detectors. There are many types of photo detectors in existence, photodiodes are used almost exclusively in optical communication applications because of their small size, suitable material, high sensitivity, and fast response time [17]. For the PIN photodiode the signal to noise ratio (SNR) is given by [18]:

$$SNR = \frac{I_p^2}{2qB(I_p + I_D) + 4KTBF_n / R_L} \quad (9)$$

Where I_p is the average photocurrent, q is the charge of an electron(C), B represents the bandwidth, I_D is the dark current, T 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 [19]

$$I_p = P_r.R \quad (10)$$

where Pr is the average optical power received to the photodetector, R is the responsivity of the photodetector.

Another main feature of FSO communication systems is the bit error rate BER [20]. The effect of fog on the Bit Error Rate BER of an FSO link is reported in [21] which correlate the atmospheric transmission with the BER. However, RZ-OOK and NRZ-OOK modulation schemes are widely used in commercial FSO communication systems because of their ease of implementation, bandwidth efficiency and cost effectiveness [22]. The relation BER and SNR for NRZ-OOK modulated signal is as follow [23, 24]:

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Table 1. System parameters used in the simulation [19, 25, 26]

Parameter	Value
Transmitter power (P_T)	5 mw
Optical efficiency of transmitter τ_t	0.75
Optical efficiency of receiver τ_r	0.75
Laser beam divergence angle θ	$2*10^{-3}$ rad
Receiver diameter	1cm
Electron charge (q)	1.6×10^{-19} C
PIN load resistance (R_L)	1kΩ
Boltzmann constant (k)	1.38×10^{-23} J.k
Temperature (T)	298K
Dark current (I_D)	10nA
Responsivity (R)	0.6A/W`
Bandwidth (B)	0.5GHz

$$BER_{NRZ-OOK} = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}}\sqrt{SNR}\right) \quad (11)$$

While BER for RZ-OOK modulated signal is given by [24, 25]:

$$BER_{L-PPM} = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}}\sqrt{SNR.\frac{L}{2}\log_2}\right) \quad (12)$$

IV. Numerical Results

In this section, using the above mentioned formulations, the simulation is carried out to study the fog attenuation channel and its effect on FSO optical wireless communication employing NRZ-OOK, L-PPM modulation techniques in the transmitter and Si PIN receiver. The values of the simulation parameters and constants are given in table (1).

1. Attenuation Coefficient for Fog Weather Condition

In FSO communication system, attenuation is an important indicator. Let us see the effect of the specific attenuation coefficient on the visibility for optical beam propagation horizontally in FSO. It is shown in Figure (1-4) Specific attenuation coefficient (dB/km) as a function of visibility (km) for wavelength 650, 850, 950, and 1550 nm under four fog attenuation models (Kim, Kruse, Al-Naboulsi Advection and Al- Naboulsi Convection). The simulation shows that we do not find any difference in Specific attenuation coefficient of the different fog model. It can be observed that the attenuation coefficient does not show wavelengths dependent behavior. The Specific attenuation coefficient has a minor difference behavior when a wavelength is increasing, furthermore, Kruse model shows sensitive for long wavelength.

2. Received signal power as a function of visibility

Let us first see the effect of the visibility on the received optical power P_r. It is shown in Fig. (5-8) curves of P_r as a function of visibility for four fog models types and four extreme cases of wavelengths. Let us assume a tolerable loss of −50 dBm beyond which the signal is not detectable at the receiver. We notice that, for λ =650 nm, the transmission range is limited to 2.2 km for Kim & Kruse models and 2.5km for Advection & Convection models. When the wavelength is increasing (λ = 850, 950 nm) decreases dramatically these range (bad visibility), obviously, it allows range limits decrease to 1.9 km for Kin & Kruse models and but 2.5 km for Advection & Convection models. When the wavelength 1550 nm is used, Kim & Kruse models can be working at bad visibility, but for Advection & convection stay about 2.5 km.

3. SNR as a function of visibility

The SNR of different fog models are compared in Fig. (9-12). The SNR increasing with increasing visibility and decreasing with increasing wavelengths. It is achieved that 1550 nm has presented the highest SNR compared with the other wavelengths under the same operating conditions. On the other hand, it can be seen that the wavelength the Kim & Kruse Models are more sensitive for fog weather, while Advection and convection models are have value about 1.2 km for different wavelengths under study.

4. BER Characteristics for FSO Communication

BER plays a crucial role in an optical communication system. We present here simulation results to compare the performance of fog attenuation under different mathematical

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models. On the other hand, we consider NRZ-OOK and 16-PPM modulation formats in the transmitter side because of its simplicity and resilience in the FSO communication system.

Figure (13-16) shows that BER for NRZ-OOK, and 16-PPM modulation formats under different fog models. In fig. (13), we notice that for BER 10^{-10}, when 16-PPM modulation is applied the visibility about 1.18 km for Kim and Kruse models and its increase for Al-Naboulsi model becomes about 1.26 km, while when a NRZ-OOK is applied, the visibility about 1.35 km for Kim and Kruse models and its increase for Al-Naboulsi model becomes about 1.45 km. It is noticed in Figure (14, 15) a significant decrease in the visibility can be achieved by using the wavelengths 850nm and 950nm. Another important simulation was

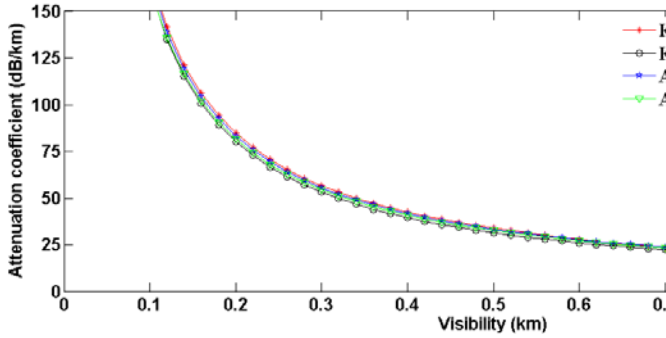

Fig (1) Specific attenuation coefficient for different models for 650 nm

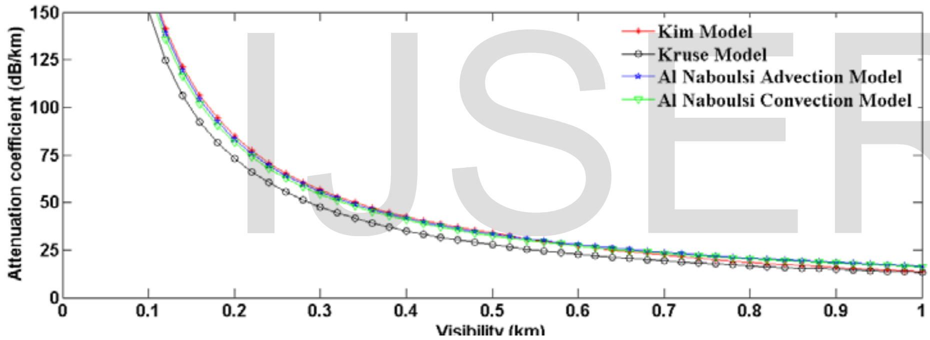

Fig (2) Specific attenuation coefficient for different models for 850 nm

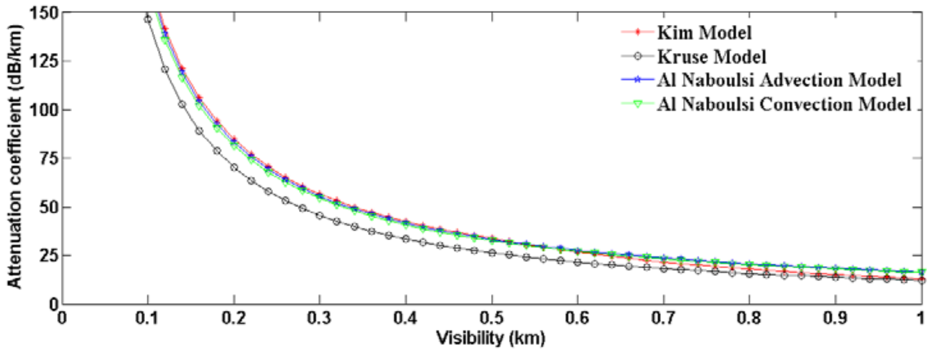

Fig (3) Specific attenuation coefficient for different models for 950 nm

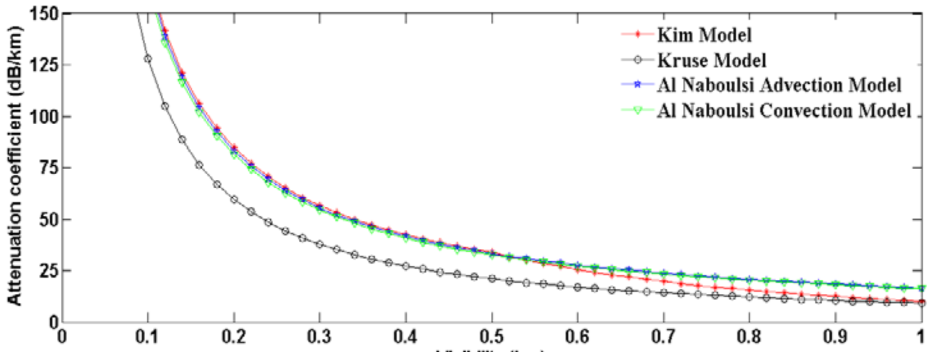

Fig (4) Specific attenuation coefficient for different models for 1550 nm

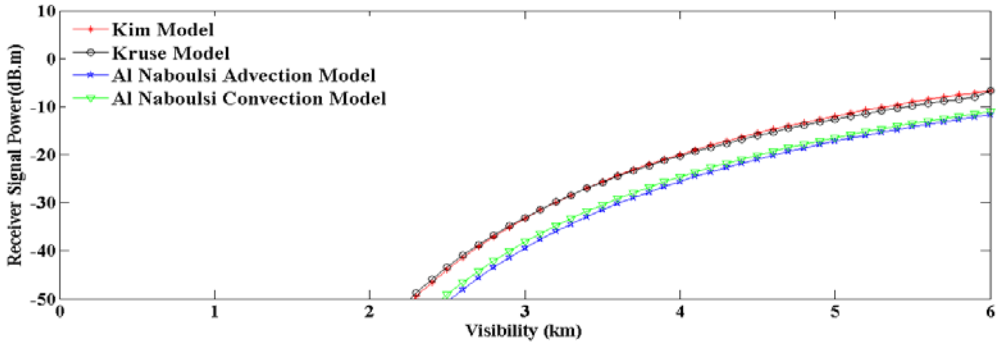

Fig (5) Received Signal Power for 650 nm

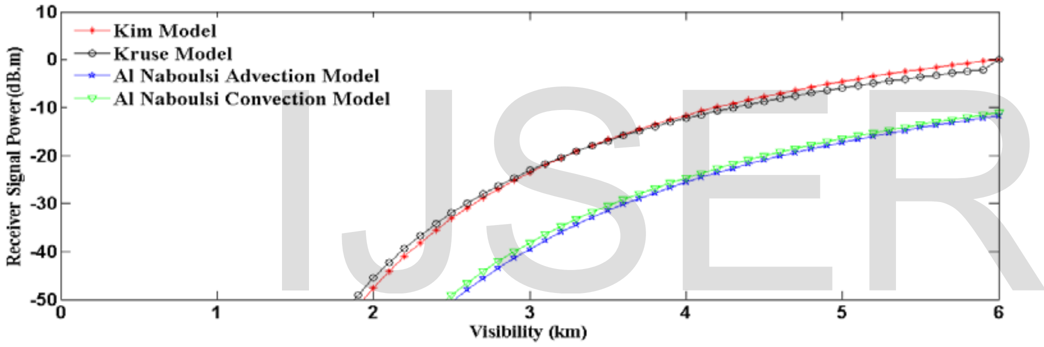

Fig (6) Received Signal Power for 850 nm

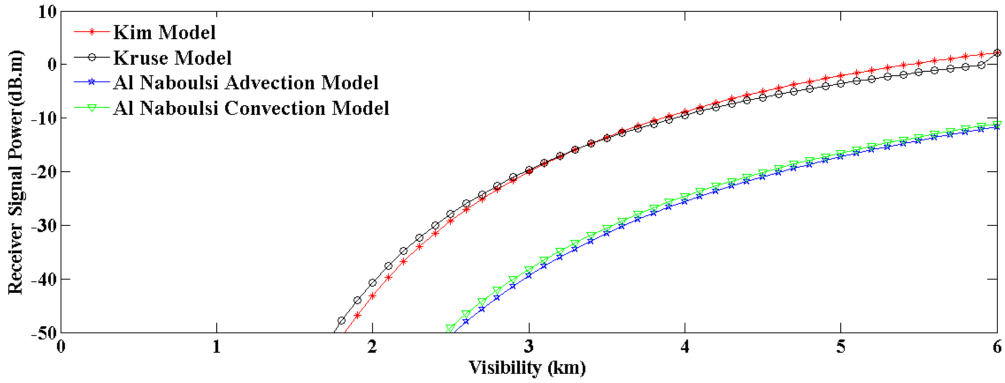

Fig (7) Received Signal Power for 950 nm

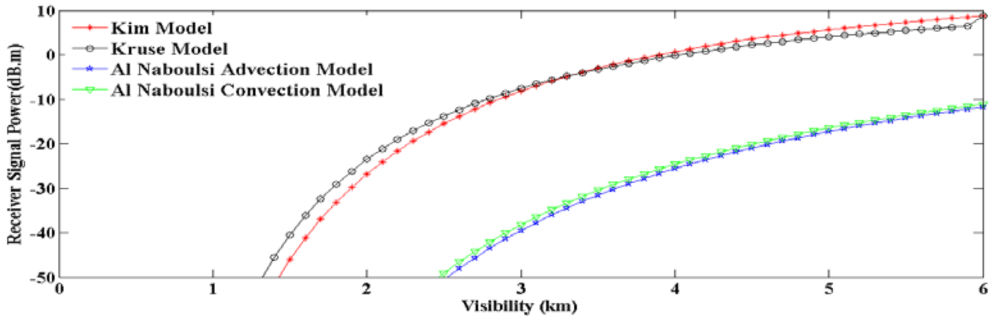

Fig (8) Received Signal Power for 1550 nm

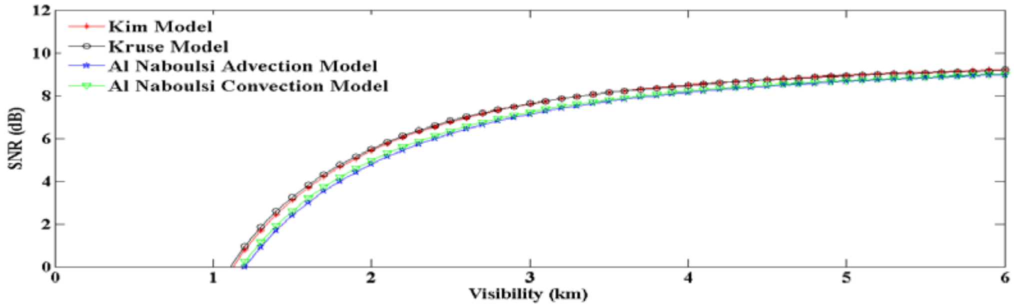

Fig (9) SNR for 650 nm

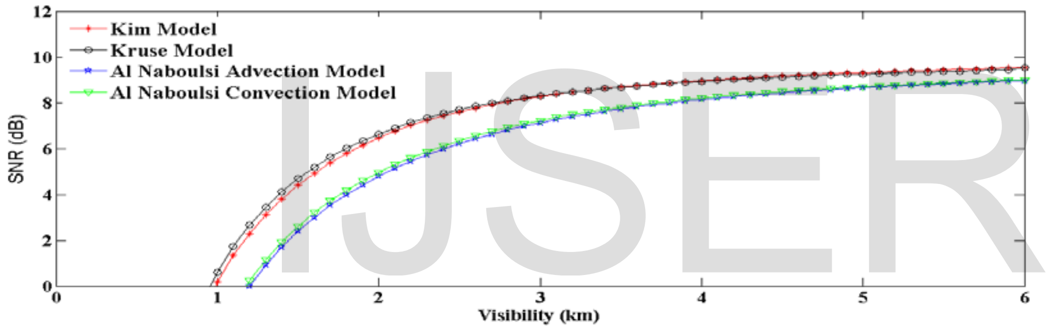

Fig (10) SNR for 850 nm

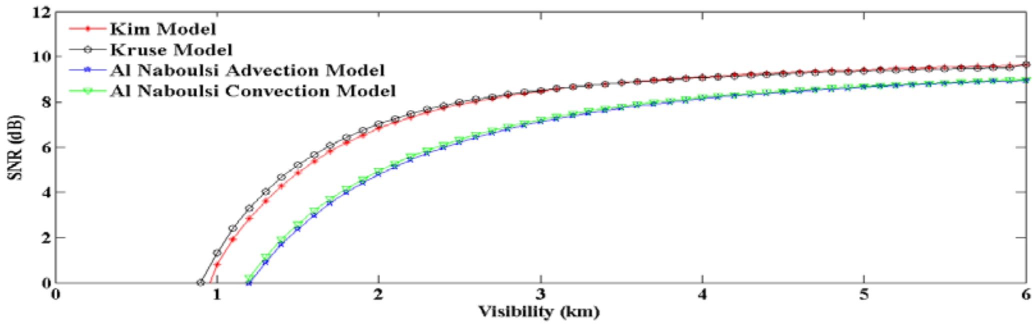

Fig (11) SNR for 950 nm

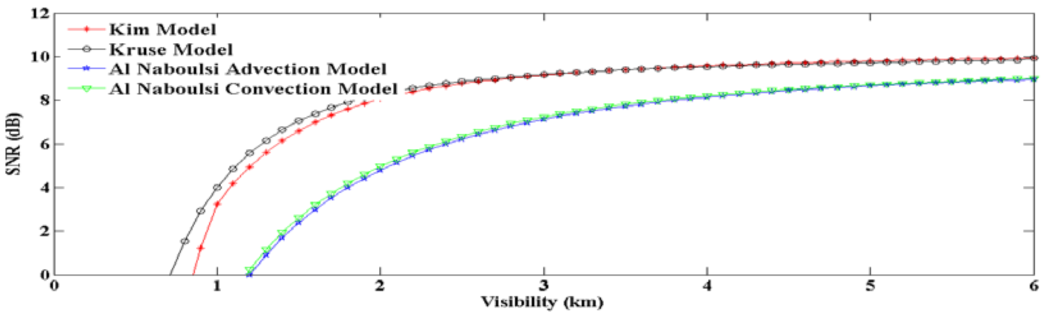

Fig (12) SNR for 1550 nm

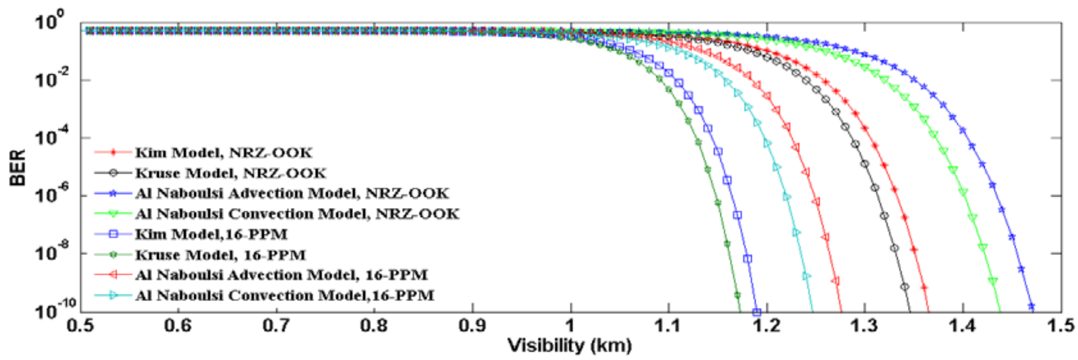

Fig (13) BER for 650 nm

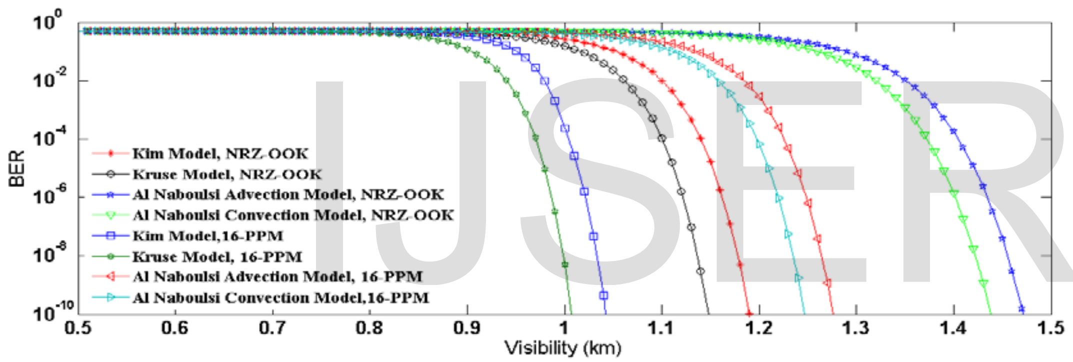

Fig (14) BER for 850 nm

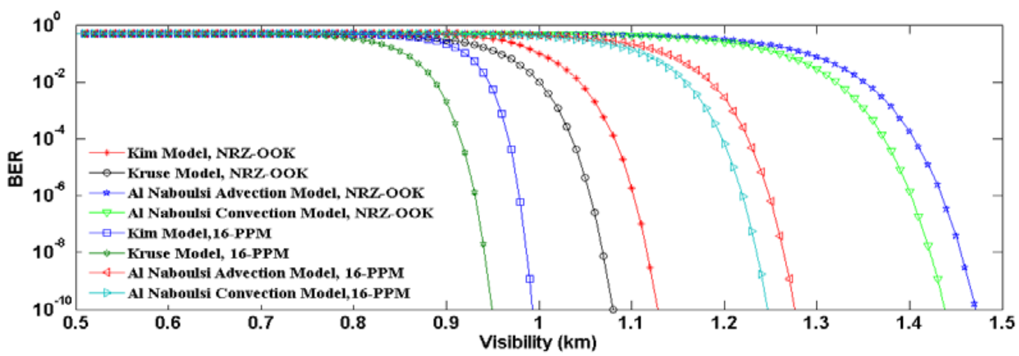

Fig (15) BER for 950 nm

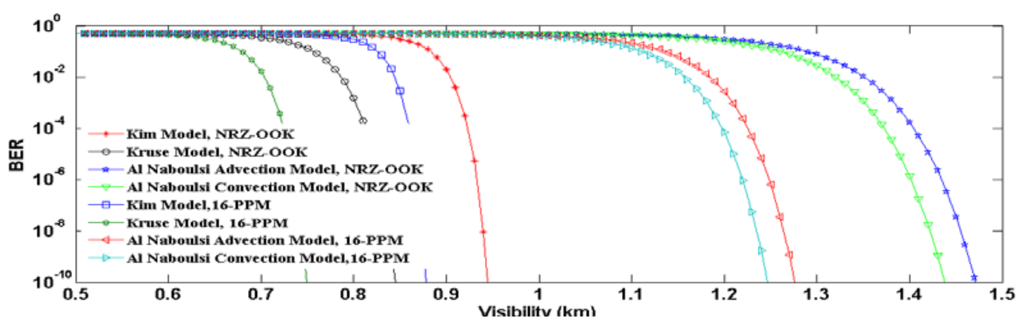

Fig (16) BER for 1550 nm

evaluated the performance of the BER for 1550nm. In Figure (16) a significant improvement in the low visibility can be achieved by using 1550nm, for 16-PPM modulation format, the maximum data transmission is about 0.75 km for Kruse and about 0.85 km for Kim model while its about 0.88 km for convection model and about 0.95 km for advection model. When we applied NRZ-OOK modulation format, the maximum data transmission is about 1.28 km for Kruse and Kim models, while, the maximum data transmission reached to 1.44 km for Advection and Convection models.

V. Conclusion

This paper provides a theoretical performance analysis of an FSO wireless communication link using NRZ-OOK and 16-PPM modulation formats in the transmitter, and Si PIN as a receiver with four mathematical models for fog attenuation. The specific attenuation coefficient of the laser beam through fog weather has a significant effect on the performance of FSO communication systems. The fog attenuation and relation with visibility are investigated, and its effect on a receiver signal power, SNR, and BER. The suitable choice of wavelength has a strong influence on the attenuation coefficient, which leads to long transmission in free space. When weather has increased visibility, this causes a decrease in attenuation coefficient. The BER characteristics of the NRZ and 16-PPM modulation formats under different fog models are studied. The results show that the wavelength 1550nm has a greater advantages than the other wavelength, therefore, a 1550nm is a more suitable wavelength compared with the other wavelengths for FSO. Furthermore, the performance of 16 - PPM is better than the NRZ-OOK, the calculations indicate that Kim and Kruse models are able to work under bad visibility. It can be observed that AL Naboulsi model (Advection and Convection) insensitive for IR wavelengths, therefore it has the same behavior when the simulation run to calculate the received signal power, SNR, and BER.

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