



Performance Evaluation of an Adaptive Hybrid FSO/RF Communication System: Impact of Weather Attenuation

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Abstract

The change in the atmospheric conditions is an effective factor that affects the free-space optical (FSO) link and the main cause of the attenuation that could lead to a link drop between the transmitter and the receiver. In this case, a backup RF link can be used to maintain the high availability of the system. This paper investigates the performance of an adaptive hybrid FSO/RF system at different wavelengths for the FSO link and different frequencies for the RF link under the effect of fog, humidity and rain. Both the received power and the bit error rate (BER) are used to evaluate the system performance. A good performance wavelength for the FSO link and frequency for the RF link are chosen to overcome attenuation and ensure that the signal is successfully delivered to the receiver by the optical link in the case of the good atmospheric conditions or by the RF link in the case of the bad atmospheric conditions. The obtained results have shown that utilizing the 1550 nm wavelength in the FSO link, the proposed system is enhanced by 49.6% than using 10 GHz in the RF link and the system was able to overcome the channel attenuation and ensure that the signal delivered to the receiver with detectable power, high data rate and low BER.

Keywords Free space optics · Radio frequency · Atmospheric conditions · Hybrid FSO/RF

1 Introduction

Free-space optical communication system (FSO) is now one of the leading wireless communication systems that depend on point-to-point line-of-sight (LOS) technique (Parkash et al. 2016). FSO system has a lot of advantages over radiofrequency (RF) system, such as it is license free and it provides high bandwidth. Besides all of this, FSO

signal can overcome a lot of technical challenges like the speed bottleneck problem (last mile connectivity), also it can be used in case of disaster recovery. RF networks can offer data rates from tens of Mbps up to several hundred Mbps (Kim et al. 2001). However, there is a limitation to their market penetration due to spectrum congestion, licensing issues and interference from unlicensed bands. Compared to RF systems, FSO can achieve higher data rates also FSO is free from any license fee and any permits. On the other hand, FSO offers a quick deployment system compared to fiber optics systems (Douik et al. 2016).

In spite of all the benefits utilizing FSO communication systems, atmospheric loss effect is considered as the main challenge facing it. This atmospheric loss can be divided into two categories: atmospheric turbulence and atmospheric attenuation. The atmospheric turbulence causes a deviation on the propagating optical radiation due to its dependency on the atmospheric pressure, wind speed and variation of refractive index (due to the temperature in homogeneity). However, limited contributions were recorded regarding atmospheric turbulence in the literature (Popoola 2009). On the other hand, the atmospheric

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attenuation is considered the most critical factor of FSO links. This attenuation occurs as a result of scattering (i.e., fog, rain and snow) (Popoola 2009) and absorption (i.e., humidity and temperature) (Ghonomie et al. 2016).

A clear LOS is required between the transmitter and the receiver ends at all times. In heavy attenuation conditions, the FSO link cannot always be preserved due to the uncontrollable outdoor environment (Popoola 2009). This leads to a decline in the system availability and can cause a link failure between the transmitter and the receiver. As a result, the need for channel diversity is emerged in order to increase the availability of the system. Consequently, a hybrid FSO/RF system would be an effective solution to overcome this low availability. The lower data rate RF link is employed as a backup link of the FSO in case that the optical link is down. RF transmission is more affected by rain, while fog is the main impact on optical transmission (Nadeem et al. 2010). Since the rain droplets absorb the heavy fog droplets, these two conditions are unlikely to happen simultaneously. This fact allows the availability of the hybrid FSO/RF system to reach 99.999% (Eslami et al. 2010).

In a previous work (Ghonomie et al. 2016), we carried out a parametric study of the effect of different weather conditions on the performance of the FSO system. In the present paper, we investigate the enhancement of the performance of the FSO system to overcome different atmospheric conditions by studying the effect of the divergence angle of the transmitter, the type of the receiver and the receiver aperture diameter. Also, we suggest the design of an adaptive hybrid FSO/RF system that can ensure that the signal is delivered to the receiver at any weather conditions. In addition, it provides high availability of the signal to the receiver under the uncontrollable weather conditions that can cause a link failure. So, using RF link as a backup of the FSO link provides a practical solution to overcome the atmospheric attenuation.

This paper proposes a new hybrid FSO/RF system model that is adaptive to attenuation due to fog, rain, humidity and temperature. The FSO system operates at 850 nm, 950 nm and 1550 nm with a non-return to zero on–off keying (NRZ-OOK) modulation technique at 10 GHz for the RF system. The impact of the channel attenuation on both the FSO and RF systems is studied and compared in order to maximize the availability of transmission at all times. In order to evaluate and optimize the proposed system performance, the bit error rate (BER) and the received power at 1 km transmission distance are investigated.

This paper is organized as follows: Sect. 2 describes the adaptive hybrid FSO/RF system. Section 3 shows attenuation model for FSO link. Section 4 introduces the attenuation model for RF link. Section 5 presents the performance evaluation of the hybrid system. Section 6 shows the results and discussion. Finally, Sect. 7 shows the main conclusions.

2 The Adaptive Hybrid FSO/RF System

The proposed system is designed in order to provide high availability at all times. The RF system is used as a backup link when the atmospheric attenuation is high enough to drop the FSO link. A block diagram for the proposed adaptive hybrid FSO/RF system is shown in Fig. 1. The system consists of three sub-systems: the laser link, the RF link and the switch. Data are transmitted at 100 Mbps full-duplex connection through the FSO link which consists of two transceivers, one at each end (see Fig. 1). If the power of the received signal (which is measured in time intervals of 5 s) is below the assigned threshold value, the proposed system automatically switches to the RF link. The data are then transmitted over the RF link until the received optical signal exceeds the threshold value. Consequently, the system switches back to the FSO link.

This paper uses the transmitter and receiver specifications of the latest FSO system technology produced by FsonaNetworks Company named SONA beam M (SONA beam M series 2017). On the other hand, an unlicensed frequency band is chosen for the backup RF link operating at 11 Mbps using 802.11b DSSS technology (Official IEEE 802.11 working group project timelines 2016).

In order to avoid the acceleration process of switching back and forth between both links, this effect is called ping-pong effect and the threshold power level to go back to the FSO link is higher than the threshold of FSO to RF. This process prevents the frequent changes in the received power level around the threshold level (Akbulut et al. 2005). At the same time, the received power level is still monitored for a quick recovery of the laser link.

3 Attenuation Model for FSO Link

According to Beer–Lambert law shown in (1) (Gagliardi and Karp 1995), the relation between the transmitted power P_t and the received power P_R is the transmission of an optical signal at wavelength λ over an atmospheric link distance L

$$\tau(\lambda, L) = \tau_s + \tau_a = \frac{P_E}{P_T} = e^{-\gamma_t(\lambda)L} \quad (1)$$

where τ is the optical transmittance, τ_s is the scattering transmittance, τ_a is the absorptive transmittance and γ_t is the overall attenuation coefficient, resulting from four individual processes (molecular and aerosol absorption coefficients in addition to molecular and aerosol scattering coefficients) (Willebrand and Ghuman 2002). The scattering can be divided into two main mechanisms depending on the relation between the air particles size and the light wavelength. When the wavelength of the light is larger

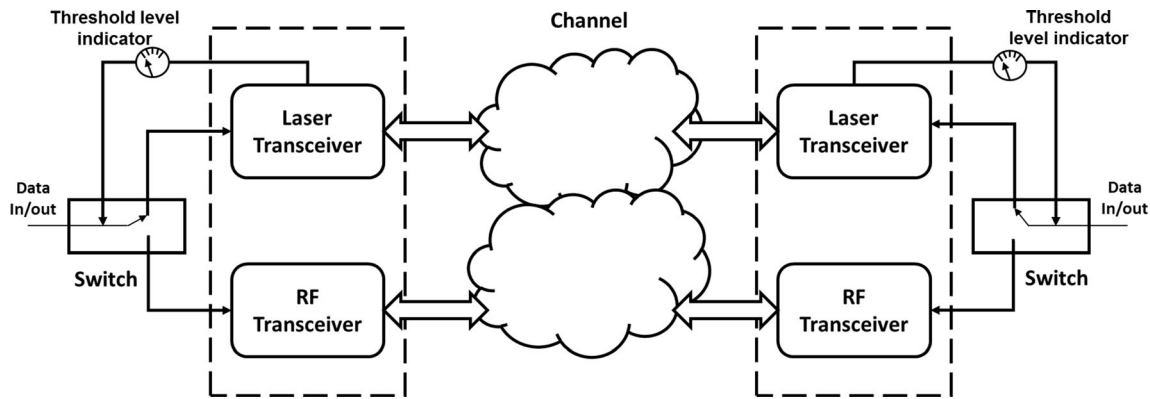


Fig. 1 The adaptive hybrid FSO/RF system

than the particle size, it is called Rayleigh scattering (Bates 1984) and is called Mie scattering if the particle size is comparable to the wavelength of radiation (Forin et al. 2010). Since the wavelength band of interest in FSO (0.5–2 μm) is close to particle size, Mie scattering is considered the dominant scattering process in FSO systems and fog is the main influence.

3.1 Fog Attenuation for FSO Link

As the fog particle size compares very much with the wavelength band of interest in FSO (0.5–2 μm), this makes fog the major photon scattered and Mie scattering the dominant scattering process in terrestrial FSO systems. The scattering transmittance is given by (2) (Forin et al. 2010).

$$\tau_s = e^{-\gamma_{fog} \cdot L} \tag{2}$$

where γ_{fog} is the attenuation of fog due to Mie scattering loss which is given by (Hemmati 2006)

$$\gamma_{fog}(\lambda) = 10^5 \int_0^\infty Q_d \left(\frac{2\pi r}{\lambda}, n' \right) \pi r^2 n(r) dr \tag{3}$$

where r is the fog particle radius in cm, Q_d is the Mie scattering efficiency, n' is the real part of the complex refractive index and $n(r)$ is the volume concentration (i.e., is the number of fog particles per unit volume per unit increment in radius). Using a mathematical derivation, γ_{fog} can be simplified to (4) (Nadeem et al. 2008a, b)

$$\gamma_{fog}(\lambda) = \frac{3.91}{V} \left(\frac{\lambda}{550} \right)^{-\delta} \tag{4}$$

where V stands for visibility in km, λ stands for wavelength in nm and the parameter δ depends on the visibility distance range. From (3), it is clear that for any meteorological conditions, the wavelength is inversely proportional to the attenuation.

There are four models to calculate δ (Nadeem et al. 2008a, b; Naboulsi et al. 2008): Kim model, Kruse model,

Al Naboulsi advection model and Al Naboulsi radiation model. In this study, Kruse model is chosen due to its dependency on wavelength as presented in (5) (Kaur and Singh 2012a, b).

$$\delta = \begin{cases} 1.6 & V > 50 \text{ km} \\ 1.3 & 6 \text{ km} < V < 50 \text{ km} \\ 0.58V^{1/3} & V < 6 \text{ km} \end{cases} \tag{5}$$

3.2 Rain Attenuation for FSO Link

In an FSO system, rain attenuation is particularly severe and is greatly dependent on various models of raindrop size distribution (Ishii et al. 2010). Raindrops increase the scattering attenuation. The transmittance due to rain is given by (Forin et al. 2010):

$$\tau_{rain} = e^{-\gamma_{rain} \cdot L} \tag{6}$$

where γ_{rain} is the rain-specific attenuation in (dB/km) and it is given by (Marshall and Palmer 1948):

$$\gamma_{rain} = \alpha R_{rain}^b \tag{7}$$

where R_{rain} is the rainfall rate in mm/h, α 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 a spherical shape which makes α and b independent of polarization. There are two models to calculate α and b , Marshal and Carbonneau models (Ali 2013).

Carbonneau’s model is used as the acceptable model because simulation found that the rain attenuation effects for Marshal model are 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. α and b for Carbonneau model are equal to 1.076 and 0.67, respectively (Ali 2013).

3.2.1 Humidity and Temperature Attenuation for FSO Link

The absorption attenuation occurs as a result of two processes: molecular absorption and aerosol absorption. The molecular absorption happened due to the effect of water, CO₂ and ozone molecules. The aerosol absorption happened due to the effect of the finely dispersed solid and liquid particles in the atmosphere.

The absorption attenuation can be calculated by assuming that variations in the transmission are caused by changes in the water content of the atmosphere. The perceptible water, ω (in mm), is given by (Weichel 1990)

$$\omega = 10^3 \rho l \quad (8)$$

where ρ is the absolute humidity in (g/m³) and l is the link distance. This value can be related to the water vapor pressure P_w (Pa) and temperature T (°C) illustrated in (Weichel 1990)

$$\rho = 2.16679 P_w / T \quad (9)$$

where the water vapor pressure P_w is given by (Weichel 1990):

$$P_w = A 10^{\left(\frac{mT}{T+n}\right)} \text{RH}/100\% \quad (10)$$

where RH is the relative humidity percentage, A , m and T_n are constants. The values of these constants are equal to 6.116441, 7.591386 and 240.7263, respectively (Vaisala 2013).

The absorptive transmittance is given by (Forin et al. 2010)

$$\begin{aligned} \tau_a &= e^{(-A_i \omega^{1/2})} & \omega < \omega_i \\ \tau_a &= k_i \left(\frac{\omega_i}{\omega}\right)^{\beta_i} & \omega > \omega_i \end{aligned} \quad (11)$$

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 (Forin et al. 2010).

4 Attenuation Model for RF Link

There is a significant attenuation that effects on the power of the RF signal due to the effect of fog, temperature and rain, but the attenuation due to humidity is negligible. This attenuation is increased due to the beam divergence, but it can be reduced by choosing the suitably transmitted frequency.

4.1 Attenuation due to Fog and Temperature on RF Link

The fog causes attenuation for frequencies higher than 10 GHz. The effect on frequencies less than 10 GHz is negligible. For small droplets less than 0.01 cm, the Rayleigh approximation is valid for frequencies below 200 GHz. The total water content per unit volume can be used to express attenuation. The specific attenuation, γ_c , is given as (Nadeem et al. 2008a, b)

$$\gamma_c = K_l M \text{ (dB/km)} \quad (12)$$

where K_l is specific attenuation coefficient [(dB/km)/(g/m³)] and M is the liquid water density in cloud or fog (g/m³).

The value of specific attenuation coefficient can be calculated using a mathematical model based on Rayleigh scattering. This model uses double-Debye model for the dielectric permittivity $\epsilon(f)$ of water (Nadeem et al. 2008a, b). The specific attenuation coefficient is given as

$$K_l = \frac{0.819f}{\epsilon'(1+\eta^2)} \frac{\text{(dB/km)}}{\text{(g/m}^3\text{)}} \quad (13)$$

where f is frequency in GHz and η is given by

$$\eta = \frac{2 + \epsilon'}{\epsilon''} \quad (14)$$

The complex dielectric permittivity of water is expressed as

$$\epsilon''(f) = \frac{f(\epsilon_0 - \epsilon_1)}{f_p \left[1 + \left(\frac{f}{f_p}\right)^2\right]} + \frac{f(\epsilon_1 - \epsilon_2)}{f_s \left[1 + \left(\frac{f}{f_s}\right)^2\right]} \quad (15)$$

$$\epsilon'(f) = \frac{(\epsilon_0 - \epsilon_1)}{\left[1 + \left(\frac{f}{f_p}\right)^2\right]} + \frac{(\epsilon_1 - \epsilon_2)}{\left[1 + \left(\frac{f}{f_s}\right)^2\right]} + \epsilon_2 \quad (16)$$

where f_p and f_s are principal and secondary relaxation frequencies in GHz, respectively, and are given by

$$f_p = 20.09 - 142 \left(\frac{300}{T} - 1\right) + 294 \left(\frac{300}{T} - 1\right)^2 \quad (17)$$

$$f_s = 590 - 1500 \left(\frac{300}{T} - 1\right) \quad (18)$$

where T is the absolute temperature. ϵ_0 is given by (19) and ϵ_1 and ϵ_2 are equal to 5.48 and 3.51, respectively.

$$\epsilon_0 = 77.6 - 103.3 \left(\frac{300}{T} - 1\right) \quad (19)$$

The visibility, V (km), in terms of liquid water content can be expressed as (Eldridge 1966)

$$V = 0.024 M^{-0.65} \quad (20)$$

where M is the liquid water content in g/m^3 .

4.2 Attenuation Due to Rain on RF Link

The rain is the most effective factor that causes a degradation on the performance of the RF communication system with frequencies above 10 GHz. The relation between specific attenuation and rain rate is given by (Nadeem et al. 2008a, b):

$$\gamma_R = k R^\alpha \text{ (dB/km)} \tag{21}$$

where k and α depend upon the frequency and microstructure of rain. There are two popular models for prediction of rain attenuation; ITU terrestrial model (Rawalpindi 2000) and Crane model (Crane 1980; Crane and Shieh 1989).

According to ITU-R model, the constants k and α in Eq. (21) are given as

$$k = \frac{(k_H + k_V + (k_H - k_V) \cos^2 \theta \cos 2\tau)}{2} \tag{22}$$

$$\alpha = \frac{(k_H \alpha_H + k_V \alpha_V + (k_H \alpha_H - k_V \alpha_V) \cos^2 \theta \cos 2\tau)}{2k} \tag{23}$$

The values of constants $k_H, k_V, \alpha_H, \alpha_V, \theta$ and τ for linear polarization (horizontal and vertical part) are given in Rawalpindi (2000).

5 Performance Evaluation of the Hybrid System

The receiver power, SNR and bit error rate (BER) are considered to evaluate the performance of the proposed adaptive hybrid FSO/RF system.

5.1 Received Power

For an FSO communication system, the received signal power P_r is given by (Kaur and Singh 2012a, b):

$$P_r = P_t \frac{D^2}{\theta_{div}^2 L^2} 10^{-\gamma L/10} \tau_{trans} \tau_{rec} \tag{24}$$

where P_t is the transmitted power, L is the link length, 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 efficiencies, respectively.

For RF communication system, by assuming having a uniform antenna at the transmitter and the receiver, the received power is given by (Toyoshima et al. 2005):

$$P_r = P_t G_t G_r \tau_{RF} \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{L^2}\right) \tau_{trans} \tau_{rec} \tag{25}$$

where P_t is the transmitted power. τ_{trans} and τ_{rec} are, respectively, the RF antenna efficiencies for the transmitter and receiver. τ_{RF} is the attenuation in RF link and is given by (Toyoshima et al. 2005):

$$\tau_{RF} = 10^{-\alpha L/10} \tag{26}$$

where α is the atmospheric attenuation in dB/km and G is the transmitter and receiver gain given by (Toyoshima et al. 2005):

$$G_{T/R} = \left(\frac{\pi D_{T/R}}{\lambda}\right)^2 \tag{27}$$

where D_T and D_R are the transmitter and receiver optical aperture diameters, respectively.

5.2 Signal-to-Noise Ratio and Bit Error Rate

For the FSO system, when using PIN photodiode, SNR is given by (Ali 2015):

$$\text{SNR} = \frac{I_p^2}{2qB(I_p + I_D) + 4KT_{PIN}BF_n/R_L} \tag{28}$$

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

The average photocurrent I_p can be expressed as (Ali 2015):

$$I_p = P_r R_{PIN} \tag{29}$$

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

The system BER calculation depends on the modulation technique. The OOK modulation technique is mostly used in FSO communication systems. BER for NRZ-OOK modulated signal is given by (Ali 2015):

$$\text{BER}_{\text{NRZ-OOK}} = \frac{1}{2} \text{erfc}\left(\frac{1}{2\sqrt{2}} \sqrt{\text{SNR}}\right) \tag{30}$$

For the RF system, the SNR is given by (Kaur and Singh 2012a, b):

$$\text{SNR}_{\text{RF}} = \frac{P_r/R_{eq}}{4kTB/R_{eq}} \tag{31}$$

where R_{eq} is the equivalent resistance, k is Boltzmann's constant, B is the equivalent noise bandwidth and T is the system absolute temperature.

The BER is given by (Kaur and Singh 2012a, b):

$$\text{BER}_{\text{RF}} = \frac{1}{2} \operatorname{erfc} \left(\frac{1}{2\sqrt{2}} \sqrt{\text{SNR}_{\text{RF}}} \right) \quad (32)$$

6 Results and Discussion

Simulation is carried out by using MATLAB and OptiSystem simulation programs to show the effect of fog, rain, temperature and humidity on FSO and RF systems when applying NRZ-OOK modulation technique in the transmitter and PIN photodiode is used in the FSO receiver. Kruse model of fog attenuation calculation for FSO link is chosen in simulation due to its wavelength dependency, while the values of the visibility, temperature, relative humidity and rainfall rate are the average values in Alexandria, Egypt, in the period from January 2017 to December 2017. The performance of FSO system is evaluated by the received optical power and BER of the system. This comparative study is carried out between FSO and RF links in the proposed adaptive hybrid system to show the possibility of using the RF link as a backup to FSO link showing the effect of combined attenuation of fog, humidity, temperature and rain. All the parameters values of the proposed systems are illustrated in Tables 1 and 2.

Table 1 Operating parameters of the FSO system

Operating parameter	Value
Transmitter power (P_t)	5 mW
Laser beam divergence angle (θ_{div})	1 mrad
Transmitter efficiency (τ_{trans})	0.9
Receiver efficiency (τ_{rec})	0.9
Wavelength (λ)	850, 950 and 1550 nm
Link length (L)	$0.1 \text{ km} \leq L \leq 1 \text{ km}$
Visibility (V)	1 km
Average atmosphere temperature (T)	20 °C
Average atmosphere relative humidity (RH)	67.9%
Rain rate (R_{rain})	18.3 mm/h
Receiver sensitivity (N_b)	− 30 dBm
Data rate (R)	100 Mbps
PIN load resistance (R_L)	1 kΩ
Boltzmann constant (k)	$1.38 \times 10^{-23} \text{ J K}$
Receiver aperture diameter	15 cm
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

Table 2 Parameters values for an RF communication system

Operating parameter	Value
Transmitter power (P_t)	5 mW
Transmitter efficiency (τ_{trans})	0.5
Receiver efficiency (τ_{rec})	0.7
Wavelength (λ)	3 cm (10 GHz frequency)
Transmitter antenna diameter (D_T)	0.18 m
Receiver antenna diameter (D_R)	5 m
Receiver sensitivity	− 110 dBm
Equivalent resistance (R_{eq})	50 k Ω
System temperature (T)	290 K

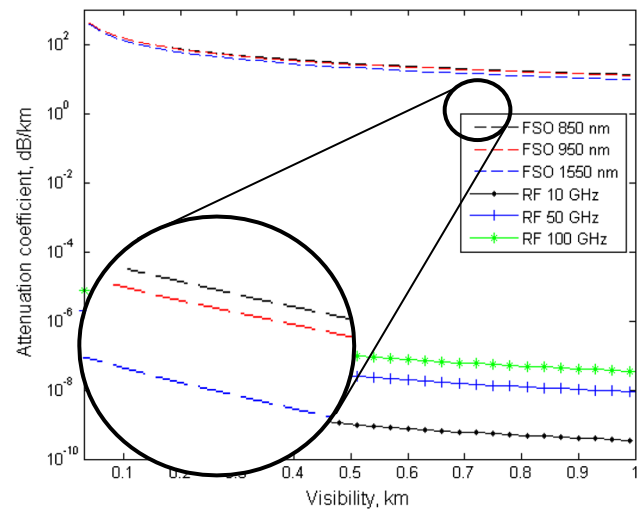


Fig. 2 Variation of attenuation coefficient with visibility for FSO and RF at frequencies greater than 10 GHz up to 200 GHz at 20 °C

Figure 2 shows the fog attenuation in both links with the visibility. The Kruse model has been used and is simulated for the fog of FSO at 850 nm, 950 nm and 1550 nm.

A great difference of fog attenuation between the two links can be observed. However, it is alarming that a backup link of 100 GHz can suffer from attenuation more than that at lower frequencies.

It can be seen that for very low visibility, fog attenuation for higher frequencies is significant and up to the extent that these frequencies no more compete the requirement of backup link. If availability is concerned, low frequencies are preferred as a backup link. On the other hand, it is clear that the attenuations of the FSO wavelengths are very comparable and appears to be higher than the RF frequencies with a priority for 1550 nm wavelength among the other wavelengths with lower attenuation.

Figure 3 shows that the behavior of the RF and FSO links is almost the same. It can clearly be seen from Eq. (7) also that the attenuation due to rain on the FSO link did not

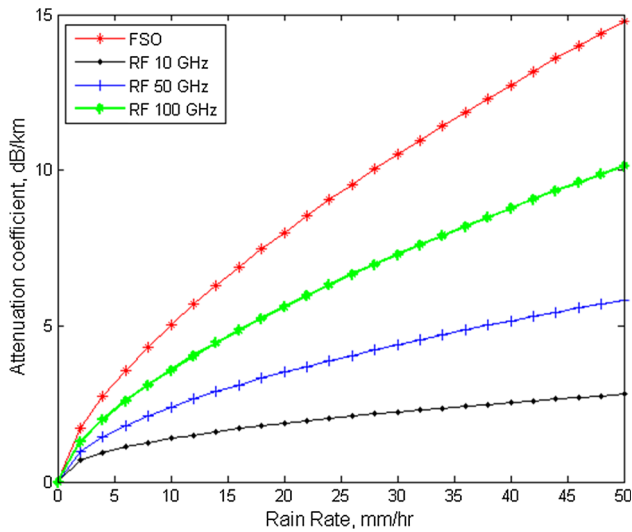


Fig. 3 Specific attenuation with rain rate for FSO and RF at frequencies 10 GHz, 50 GHz and 100 GHz

affect by the changing in the wavelength of the beam but it depends on the rain rate. On the opposite, the RF link’s attenuation gives respond with changing the frequencies and has a lower attenuation than it is in the FSO link. It is obvious that the change in the rain rate does not significantly affect on the lower frequencies, and 10 GHz frequency gives the lower attenuation among other frequencies. This is in a fair agreement with the work of Nadeem et al. (2008a, b).

Simulation is carried out for several values of temperature and relative humidity to get the attenuation for 1 km path FSO link. The obtained results can be observed in Fig. 4. It is clear that the attenuation decreases with the

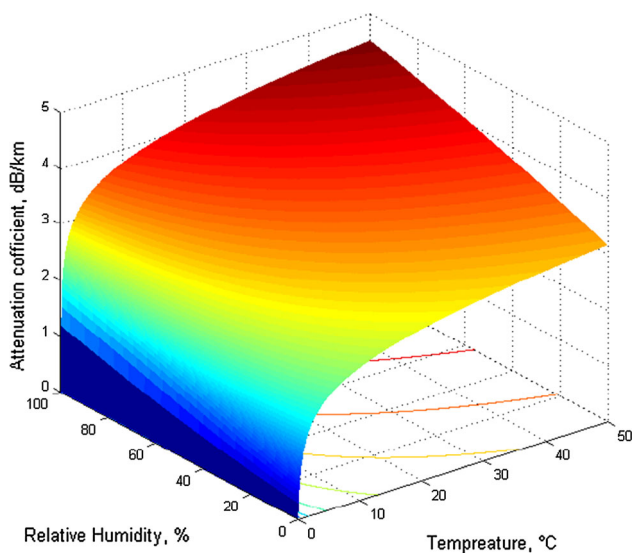


Fig. 4 Attenuation coefficient due to temperature and relative humidity

decreasing of relative humidity and temperature values. It is also clear that the effect of temperature and humidity, due to absorption and scattering, is important and cannot be neglected. The total attenuation is in the range 0–4.7 dB/km.

Figure 5 is graphical illustration from Fig. 4 and shows the attenuation due to relative humidity at specific temperature 20 °C. It is clear that the attenuation slightly rises with the increase in the relative humidity.

The received power for both FSO and RF links with the link distance is illustrated in Fig. 6. The simulation is carried out at a transmitted power of 5 mW for both links and with RF receiver sensitivity of – 110 dBm for a combined effect of fog, humidity, temperature and rain.

It is clear that the received power of the RF system is lower than that of the FSO system. But, this difference in the received power will not prevent the use of RF as a backup link because of using receiver sensitivity for RF system – 110 dBm. So, the RF received power will be detected. Figure 7 displays the BER with link distance for RF and FSO links. It can be observed that BER at 3 cm wavelength (10 GHz) for RF link is lower than that of the 850 nm and 950 nm for FSO link and is approximately the same as 1550 nm wavelength. But the BER for the RF system has a different behavior than FSO system.

This indicates that in spite of the great difference between the attenuation at RF system and FSO system using 1550 nm wavelength, the 1550 nm wavelength can reach an acceptable BER for 1 km like RF signal.

Figure 8 shows that increasing the rain rate leads to increase in the BER for both FSO and RF, but its effect is greater on FSO wavelengths than the used RF frequency.

Figure 9 illustrates the effect of changing the temperature. It is obvious that increasing the temperature causes a slight increase in the BER of the FSO wavelengths with

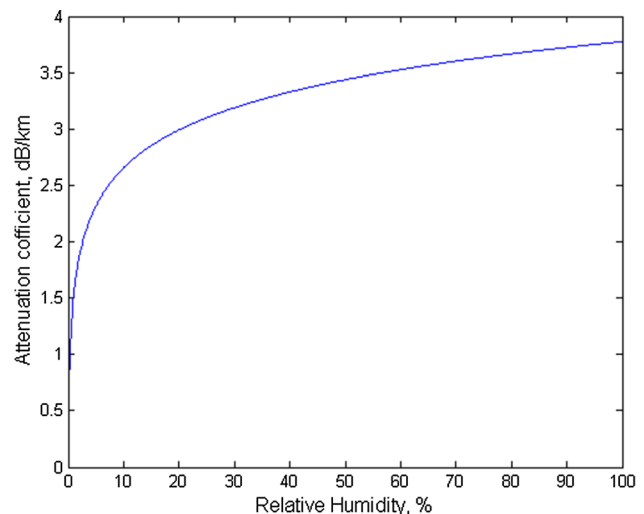


Fig. 5 Attenuation coefficient due to relative humidity at 20 °C

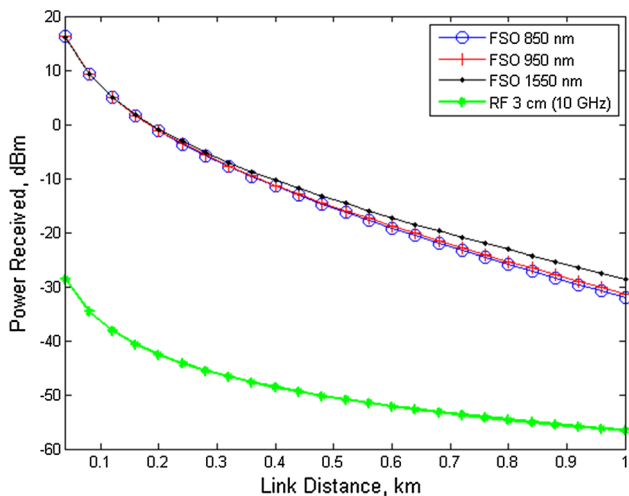


Fig. 6 Comparison of received power with link distance: combined effect of fog, rain, humidity and temperature on FSO and RF links

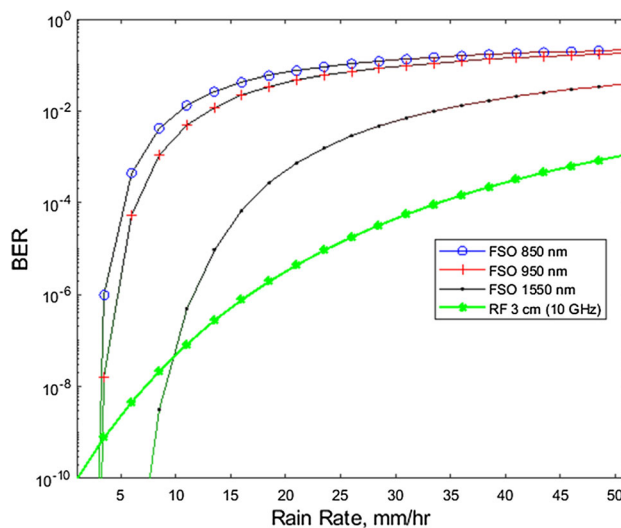


Fig. 8 Comparison of BER with rain rate for FSO and RF

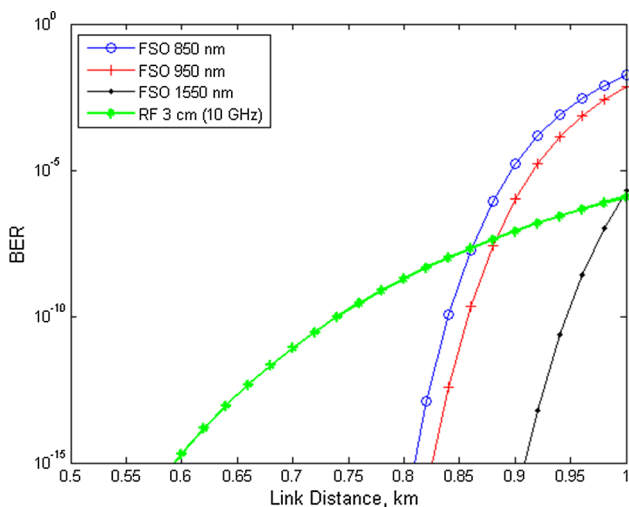


Fig. 7 Comparison of BER with link distance: combined effect of fog and rain for FSO and RF

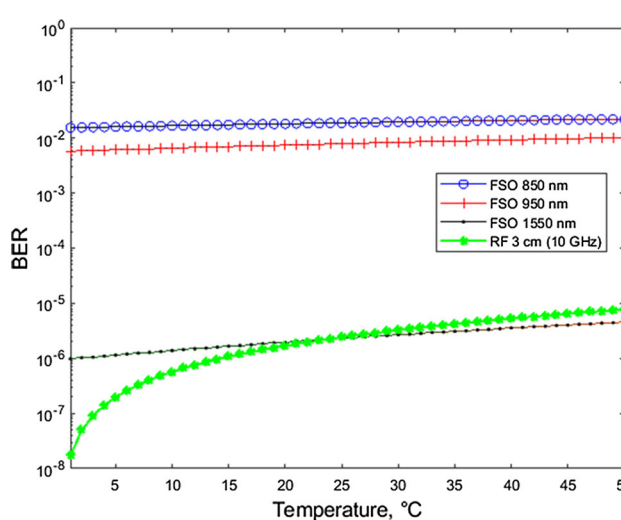


Fig. 9 BER versus temperature for FSO and RF

less BER values for 1550 nm wavelength. At the same time, its effect is greater on the RF signal with a BER approximately comparable to 1550 nm wavelength at the middle of the temperature range. Starting from 27 °C, the BER increases slightly more than the 1550 nm wavelength.

The effect of changing the relative humidity is illustrated in Fig. 10. It is clear that increasing the relative humidity has a very small effect on the BER of the FSO wavelengths.

7 Conclusion

This paper presents a theoretical analysis for the attenuation in an FSO and RF communication channel due to fog, rain and humidity. The performance is studied using the

NRZ-OOK modulation technique. The specific attenuation coefficient due to fog has a significant effect on the performance of FSO communication systems which can reach visibility of 1 km up to 50 dB/km at 1550 nm wavelength and for RF system can reach up to 8×10^{-9} dB/km at 10 GHz frequency. But for RF communication system, the rain is the most effective atmospheric factor to its performance and the attenuation due to rain can reach to 14.8 dB/km for FSO system and 2.8 dB/km at 10 GHz frequency for RF system. The receiver signal power and BER are investigated to evaluate the performance of the hybrid system. Selecting a suitable wavelength for the FSO system and frequency for RF system has a strong impact on the attenuation coefficient to achieve minimum BER and a detectable received power, which leads to longer transmission distances. The obtained results show that the

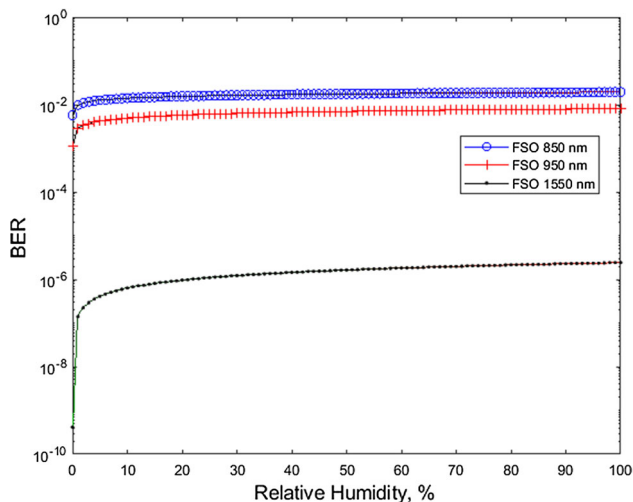


Fig. 10 BER versus relative humidity for FSO

1550 nm has greater advantages than the other wavelengths for FSO system and also 10 GHz has greater advantages than the other frequencies for RF system. This leads to an increase in transmission distance.

The received power in the RF system is lower than in the FSO system by approximately 50%, but it can be detected because that the receiver sensitivity of RF is lower than the sensitivity of the FSO link. The received power at link distance 1 km for FSO system is -28.52 dBm at 1550 nm wavelength and equal to -56.59 dBm for RF system at 10 GHz frequency. The BER at 1 km link length of the RF link using 3 cm wavelength (10 GHz) is approximately the same as the BER of FSO system using 1550 nm wavelength. In case of RF, using 3 cm the BER is equal to 1.23×10^{-6} and is equal to 1.96×10^{-6} for 1550 nm wavelength of FSO. The BER is less than that at 850 nm and 950 nm wavelengths which are equal to 1.82×10^{-4} and 7.5×10^{-3} , respectively. So, the RF system can be used as a backup for the FSO system in the adaptive hybrid FSO/RF system to achieve a very high availability system.

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