

# Effect of Clear Atmospheric Turbulence on Quality of Free Space Optical Communications in Western Asia

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## 1. Introduction

The Free Space Optical (FSO) communication is also known as Wireless Optical Communication (WOC), Fibreless, or Laser Communication (Lasercom). FSO communication is one of the various types of wireless communication which witnesses a vast development nowadays. FSO provides a wide service and requires point-to-point connection between transmitter and receiver at clear atmospheric conditions. FSO is basically the same as fiber optic transmission. The difference is that the laser beam is collimated and sent through atmosphere from the transmitter, rather than guided through optical fiber [1]. The FSO technique uses modulated laser beam to transfer carrying data from a transmitter to a receiver. FSO is affected by attenuation of the atmosphere due to the instable weather conditions. Since the atmosphere channel, through which light propagates is not ideal.

In this study we will take republic of Yemen as case study. In some mountainous areas in Yemen, it is difficult to install the technique of fiber optics. But FSO technique will solve this problem with same proficiency and quality provided by fiber optics. FSO systems are sensitive to bad weather conditions such as *fog, haze, dust, rain and turbulence*. All of these conditions act to attenuate light and could block the light path in the atmosphere. As a result of these challenges, we have to study weather conditions in detail before installing FSO systems. This is to reduce effects of the atmosphere also to ensure that the transmitted power is sufficient and minimal losses during bad weather.

This chapter aims to study and analyze the atmosphere effects on the FSO system propagation in the Republic of Yemen weather environment. The study is focused more on the effects of haze, rain and turbulence on the FSO systems.

The analysis conducted depends basically on statistical data of the weather conditions in Yemen obtained from the Civil Aviation and Meteorology Authority (CAMA) for visibility and wind velocity and from the Public Authority for Water Resources (PAWR) for the rainfall rate intensity. So, the prominent objectives of this work are:

1. Calculating the scattering coefficient, atmospheric attenuation, total attenuation in the hazy and rainy days and scintillation at the clear days.

2. Studying the performance of FSO system at wavelengths 780 nm, 850 nm and 1550 nm, beam divergence angle, transmitter and receiver diameter apertures and transmission range.

The scope of this chapter focuses on studying and analyzing of FSO propagation under weather conditions in Yemen environment for outdoor system. The atmospheric effects divided into two kinds: atmospheric attenuation and atmospheric turbulence. Atmospheric attenuation due to Mie scattering is related to the haze and it is a function of the visibility, and attenuation due to rainfall independent on wavelength. The atmospheric turbulence is due to variance of refractive index structure.

There are three factors which enable us to test the FSO performance as: design, uncontrollable and performance. Design factors are relating to FSO design such as light power, wavelength, receiver and transmitter aperture diameter, link range and detector sensitivity. Uncontrollable elements such as rainfall elements include rainfall rate and raindrop radius, haze element include visibility and turbulence element include refractive index structure. Performance of system was tested during the rainy days and hazy days which can be calculated from the effect of scattering coefficient, atmospheric attenuation and total attenuation. However, the system performance in the clear days can be calculated from the effect of variance.

The remainder of this chapter is organized as follow: Discusses briefly the background of FSO. The concept of and the several stages of FSO transceiver are explained briefly. Illustrate the losses of FSO system due to atmosphere channel and geometric losses. Defining the aerosols and visibility and how they effect on FSO system were introduced. Beer's law which describes attenuation of atmospheric channel due to absorption and scattering coefficient was introduced. The atmospheric attenuation types are explained. Stroke's law which describes scattering coefficient due to rainfall was introduced. Geometrical loss and total attenuation are discussed. Represent the analytical study of Yemeni environment. Scattering coefficient and attenuation in hazy days at average and low visibility at three wavelengths (780 nm, 850 nm and 1550 nm) were introduced. The atmospheric attenuation at the lowest visibility conditions was plotted with the link range. Scattering coefficient and atmospheric attenuation in rainy days were plotted once versus rainfall rate and once again versus raindrop radius. Scattering coefficient and atmospheric attenuation to haze in Sana'a, Aden and Taiz cities were calculated. The geometric loss for two commonly used designs of transceivers was evaluated. The conclusion is done based on the overall findings of this work.

## **2. Fundamental of free space optical communication**

FSO is a technique used to convey data carried by a laser beam through the atmosphere. While FSO offers a broadband service, it requires Line of Sight (LOS) communication between the transmitter and receiver as shown in the Fig. (1)[1].

The atmosphere has effects on the laser beam passing through it, so the quality of data received is affected. To reduce this effect, the fundamental system components must be designed to adopt with the weather conditions. This design is mostly related to transmitter and receiver components. In the following subsection, we will tackle discuss the components and the basic system of FSO.

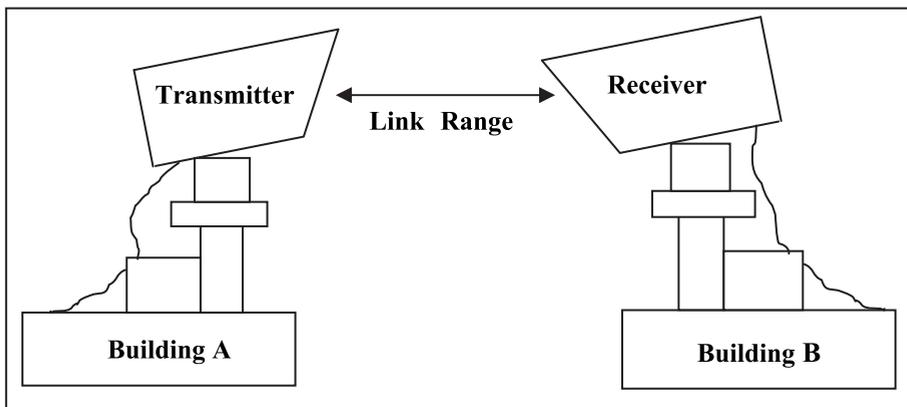


Fig. 1. Schematic showing FSO Transmitter and Receiver LOS.

### 2.1 FSO communication subsystem

FSO communication is a line of sight technology that uses laser beam for sending the very high bandwidth digital data from one point to another through atmosphere. This can be achieved by using a modulated narrow laser beam lunched from a transmission station to transmit it through atmosphere and subsequently received at the receiver station. The generalized FSO system is illustrated in Fig. (2), it is typically consists of transmitter, FSO channel and a receiver.

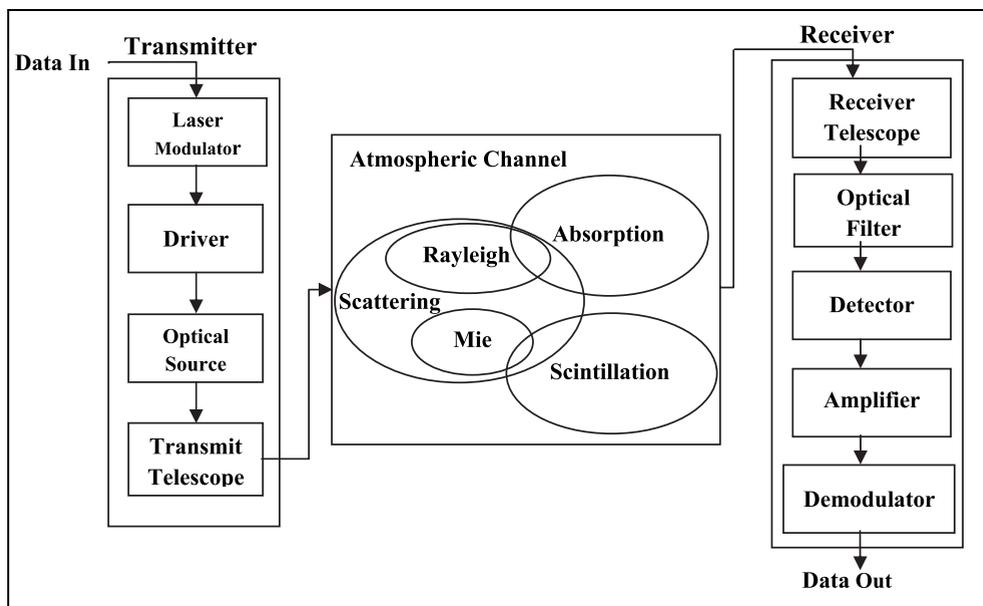


Fig. 2. Block Diagram of a Terrestrial FSO System.

### a. Transmitter

Transmitter transforms the electrical signal to an optical signal and it modulates the laser beam to transfer carrying data to the receiver through the atmosphere channel. The transmitter consists of four parts as shown in Fig. (2): laser modulator, driver, optical source and transmit telescope.

- **Laser modulator**

Laser modulation means the data were carried by a laser beam. The modulation technique can be implemented in following two common methods: internal modulation and external modulation [2].

**Internal modulation:** is a process which occurs inside the laser resonator and it depends on the change caused by the additive components and change the intensity of the laser beam according to the information signal.

**External modulation:** is the process which occurs outside the laser resonator and it depends on both the polarization phenomena and the refractive dualism phenomenon.

- **Driver**

Driver circuit of a transmitter transforms an electrical signal to an optical signal by varying the current flow through the light source.

- **Optical source**

Optical source may be a laser diode (LD) or light emitting diode (LED), which used to convert the electrical signal to optical signal.

A laser diode is a device that produces optical radiation by the process of stimulated emission photons from atoms or molecules of a lasing medium, which have been excited from a ground state to a higher energy level. A laser diode emits light that is highly monochromatic and very directional. This means that the LD's output has a narrow spectral width and small output beam angle divergence. LDs produce light waves with a fixed-phase relationship between points on the electromagnetic wave. There are two common types of laser diode: Nd:YAG solid state laser and fabry-perot and distributed-feedback laser (FP and DFB) [3].

- **Laser source selection criteria for FSO**

The selection of a laser source for FSO applications depends on various factors. They factors can be used to select an appropriate source for a particular application. To understand the descriptions of the source performance for a specific application, one should understand these detector factors. Typically the factors that impact the use of a specific light source include the following [4]:

- Price and availability of commercial components
- Transmission power and lifetime
- Modulation capabilities
- Eye safety
- Physical dimensions and compatibility with other transmission media.

- **Transmitter telescope**

The transmitter telescope collects, collimates and directs the optical radiation towards the receiver telescope at the other end of the channel.

- b. FSO channel

For FSO links, the propagation medium is the atmosphere. The atmosphere may be regarded as series of concentric gas layers around the earth. Three principal atmospheric layers are defined in the homosphere [5], the troposphere, stratosphere and mesosphere. These layers are differentiated by their temperature gradient with respect to the altitude. In FSO communication, we are especially interested in the troposphere because this is where most weather phenomena occur and FSO links operate at the lower part of this layer [5].

The atmosphere is primarily composed of nitrogen ( $N_2$ , 78%), oxygen ( $O_2$ , 21%), and argon (Ar, 1%), but there are also a number of other elements, such as water ( $H_2O$ , 0 to 7%) and carbon dioxide ( $CO_2$ , 0.01 to 0.1%), present in smaller amounts. There are also small particles that contribute to the composition of the atmosphere; these include particles (aerosols) such as haze, fog, dust, and soil [6].

Propagation characteristics of FSO through atmosphere drastically change due to communication environment, especially, the effect of weather condition is strong. The received signal power fluctuates and attenuates by the atmospheric obstacles such as rain, fog, haze and turbulence in the propagation channel. The atmospheric attenuation results from the interaction of the laser beam with air molecules and aerosols along the propagation. The main effects on optical wireless communication are absorption, scattering, and scintillation [7].

- c. Receiver

The receiver optics consists of five parts as shown in Fig. 2: receiver telescope, optical filter, detector, amplifier and demodulator.

- **Receiver telescope**

The receiver telescope collects and focuses the incoming optical radiation on to the photo detector. It should be noted that a large receiver telescope aperture is desirable because it collects multiple uncorrelated radiation and focuses their average on the photo detector [8].

- **Optical filter**

By introducing optical filters that allow mainly energy at the wavelength of interest to impinge on the detector and reject energy at unwanted wavelengths, the effect of solar illumination can be significantly minimized [6].

- **Detector**

The detector also called photodiode (PD) is a semiconductor devices which converts the photon energy of light into an electrical signal by releasing and accelerating current conducting carriers within the semiconductors. Photodiodes operate based on photoconductivity principals, which is an enhancement of the conductivity of p-n semiconductor junctions due to the absorption of electromagnetic radiation. The diodes are generally reverse-biased and capacitive charged [9]. The two most commonly used photodiodes are the pin photodiode and the avalanche

photodiode (APD) because they have good quantum efficiency and are made of semiconductors that are widely available commercially [10].

- **Features of detector**

The performance characteristics indicate how a detector responds to an input of light energy. They can be used to select an appropriate detector for a particular application. To understand the descriptions of detector performance and to be able to pick a detector for a specific application, one should understand these detector characteristics. In general, the following properties are needed:

- A high response at the wavelength to be detected.
- A small value for the additional noise is introduced by the detector.
- Sufficient speed of response.

## 2.2 FSO system

FSO system refers to the transmission of modulated visible or infrared (IR) beams through the atmosphere to obtain broadband communications. This technique requires clear line of site between the transmitter and the receiver. FSO system provides higher bandwidth at faster speed. The elements of FSO designed which must be considered by a prudent user are wavelength, beam divergence angle, aperture diameter and range.

### 2.2.1 Wavelength

To select the best wavelength to use for free-space optical communication systems, you must consider several factors, such as availability of components, eye safety considerations, required transmission distance, price, and so on. The availability of components is light sources and detectors [4]. Eye safety is one of the most important restrictions to the optical power level emitted by a wireless IR transmitter. Lasers of much higher power can be used more safely with 1550 nm systems than with 850 nm and 780 nm systems. This is because wavelengths is less than about 1400 nm focused by the human cornea into a concentrated spot falling on the retina as shown in Fig. (3), which can cause eye damage.

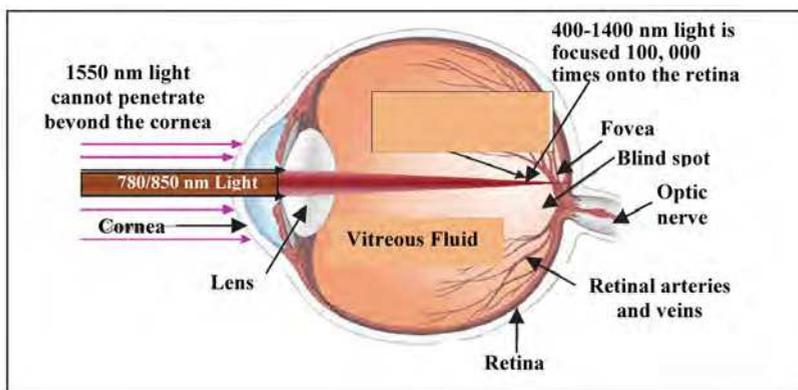


Fig. 3. Penetration of Light into Eyeball.

The allowable safe laser power is about 50 times higher at 1550 nm. This factor, 50 is important as it provides up to 17 dB additional margin, allowing the system to propagate over longer distances, through heavier attenuation, and to support higher data rates [11]. However, 1550 nm systems are at least 10 times more expensive than 850 nm systems [16]. The highest data rate available with commercial 850 nm systems is 622 Mbps, and 2.5 Gbps for 1550 nm systems. Table (1) illustrates the maximum Permissible Exposure (MPE) limited for unaided viewing, in case of 850 nm and 1550 nm [11].

Wavelength	Maximum Permissible Exposure (MPE)
850 nm	2 mW/cm <sup>2</sup>
1550 nm	100 mW/cm <sup>2</sup>

Table 1. Maximum Permissible Exposure Limited for "unaided viewing".

### 2.2.2 Beam divergence

Beam divergence purposely allows the beam to diverge or spread. The advantage using narrow beam in FSO system generates much higher data rates and increases the security. Laser generated with extreme narrow light can be easily modulated with voice and data information. The beam spread is dependent on the beam divergence angle and transmission range. Typically, 1 mrad to 8 mrad beam divergence spreads 1 to 8 m at distance of 1 km. To avoid spreading of a large beam, it is better to use narrow beam divergence such as 1 mrad [12-14].

### 2.2.3 Aperture diameter

In FSO system a smaller diameter of transmitter and a larger diameter of receiver aperture are needed to establish high data rate communication links. The diameter aperture of the transmitter and receiver must be adequate for the weather conditions. When the laser beam propagates through atmosphere, the beam is spreading, at a distance L from the source, due to the turbulence. If the turbulence cell is larger than the beam diameter, and the diameter of receiver aperture is small, then the beam bends and it can cause the signal to complete missing the received unit. A large size of diameter aperture of receiver is able to reduce turbulence effect on FSO [12][15]. Two particular design specifications are made in Table (2) due to particular implementation especially based on the existing product available in the industry [12].

Design	Diameter of transmitter aperture	Diameter of receiver aperture
Design 1	18 cm	18 cm
Design 2	3.5 cm	20 cm

Table 2. Diameter of Transmitter and Receiver Aperture of an FSO System.

### 2.2.4 Range

Distance between a transmitter and a receiver impacts the performance of FSO systems in three ways. First, even in clear weather conditions such as scintillation, the beam diverges and the detector element receives less power. Second, the total transmission loss of the beam

increases with increasing distance. Third, scattering and absorption effect accumulates with longer distances. Therefore, the value for the scintillation fading margin in the overall power budget will increase to maintain a predefined value for the BER. Most commercially available FSO systems are rated for operation between 25–5000 m, with high-powered military and satellite systems capable of up to 2000 km. Most systems rated for greater than 1 km incorporate three or more lasers operating in parallel to mitigate distance related to issues. It is interesting to note that in the vacuum of space, FSO can achieve distances of thousands of kilometers [4].

### 3. Formulations

Free space optical communication link requires a good understanding of the atmosphere as the laser beam has to propagate through it. The atmosphere not only attenuates the light wave but also distorts and bends it. Attenuation is primarily the result of absorption and scattering by molecules and particles (aerosols) suspended in the atmosphere. Distortion, on the other hand, is caused by atmospheric turbulence due to index of refraction fluctuations. Attenuation affects the mean value of the received signal in an optical link whereas distortion results in variation of the signal around the mean. Often, atmospheric attenuation can be the limiting factor in an optical communication link through the atmosphere [16].

#### 3.1 Aerosols

Aerosols are particles suspended in the atmosphere such as fog, haze, dust and smog, and they have diverse nature, shape, and size. Aerosols can vary in distribution, constituents, and concentration. The larger concentration of aerosols is in the boundary layer (a layer up to 2 km above the earth surface). Above the boundary layer, aerosol concentration rapidly decreases [3].

Scattering is the main interaction between aerosols and a propagating beam. Because the sizes of the aerosol particles are comparable to the wavelength of interest in optical communications, Mie scattering theory is used to describe aerosol scattering [17].

Type	Radius ( $\mu\text{m}$ )	Concentration ( in $\text{cm}^{-3}$ )
Air molecules	$10^{-4}$	$10^{19}$
Aerosol	$10^{-2}$ to 1	10 to $10^3$
Fog	1 to 10	10 to 100
Cloud	1 to 10	100 to 300
Raindrops	$10^2$ to $10^4$	$10^{-5}$ to $10^{-2}$
Snow	$10^3$ to $5 \times 10^3$	N/A
Hail	$5 \times 10^3$ to $5 \times 10^4$	N/A

Table 3. Radius Ranges for Various Types of Particles.

Such a theory specifies that the scattering coefficient of aerosols is a function of the aerosols, their size distribution, cross section, density, and wavelength of operation. The different types of atmospheric constituents' sizes and concentrations of the different types of atmospheric constituents are listed in Table (3) [6], [18].

### 3.2 Visibility runway visual range (RVR)

Visibility defined as (Kruse model) means of the length where an optical signal of 550 nm is reduced to 0.02 of its original value. It is characterized by the transparency of the atmosphere, estimated by a human observer. Visibility is a useful measure of the atmosphere containing fog, smog, dust, haze, mist, clouds and other contaminating particles. Thick fog can reduce visibility down to a few meters; and maritime mist and clouds can affect visibility in the same way [19].

Low visibility will decrease the effectiveness and availability of FSO systems, and it can occur during a specific time period within a year or at specific times of the day. Low visibility means the concentration and size of the particles are higher compared to average visibility. Thus, scattering and attenuation may be caused more in low visibility conditions [20]. Attenuation can reach hundreds of dB per km for low visibility values, and is higher at shorter wavelength [21]. Low visibility and the associated high scattering coefficients are the most limiting factors for deploying FSO systems over longer distances [4].

### 3.3 Atmospheric attenuation

Atmospheric attenuation is defined as the process whereby some or all of the electromagnetic wave energy is lost when traversing the atmosphere. Thus, atmosphere causes signal degradation and attenuation in a FSO system link in several ways, including absorption, scattering, and scintillation. All these effects are time-varying and will depend on the current local conditions and weather. In general, the atmospheric attenuation is given by the following Beer's law Eq. (1) [22]:

$$\tau = \exp(-\beta L) \quad (1)$$

Where:

$\tau$ : is the atmospheric attenuation.

$\beta$ : is the total attenuation coefficient given as:

$$\beta = \beta_{abs} + \beta_{scat} \quad (2)$$

$L$ : is the distance between ( $T_x$ ) and ( $R_x$ ) in kilometer.

$\beta_{abs}$ : is the molecular and aerosol absorption.

$\beta_{scat}$ : is the molecular and aerosol scattering.

### 3.4 Absorption

Absorption is caused by the beam's photons colliding with various finely dispersed liquid and solid particles in the air such as water vapor, dust, ice, and organic molecules. The aerosols that have the most absorption potential at infrared wavelengths include water,  $O_2$ ,  $O_3$ , and  $CO_2$ . Absorption has the effect of reducing link margin, distance and the availability of the link [4].

The absorption coefficient depends on the type of gas molecules, and on their concentration. Molecular absorption is a selective phenomenon which results in the spectral transmission

of the atmosphere presenting transparent zones, called atmospheric transmission windows [5], and shown in Fig. (4), which allows specific frequencies of light to pass through it. These windows occur at various wavelengths. The atmospheric windows due to absorption are created by atmospheric gases, but neither nitrogen nor oxygen, which are two of the most abundant gases, contribute to absorption in the infrared part of the spectrum [6].

It is possible to calculate absorption coefficients from the concentration of the particle and the effective cross section such as shown in Eq. (3) [2]:

$$\beta_{abs} = \alpha_{abs} N_{abs} \left[ \frac{1}{km} \right] \quad (3)$$

Where:

$\alpha_{abs}$ : is the effective cross section of the absorption particles [ $km^2$ ].

$N_{abs}$ : is the concentration of the absorption particles [ $1/km^3$ ].

The absorption lines at visible and near infrared wavelengths are narrow and generally well separated. Thus, absorption can generally be neglected at wavelength of interest for free space laser communication [22]. Another reason for ignoring absorption effect is to select wavelengths that fall inside the transmittance windows in the absorption spectrum [23].

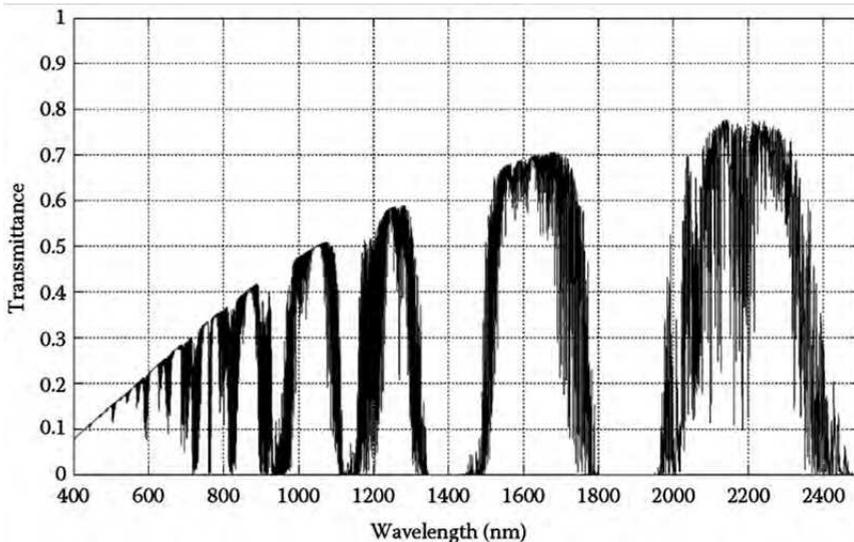


Fig. 4. Atmospheric Transmittance Window with Absorption Contribution.

### 3.5 Scattering

Scattering is defined as the dispersal of a beam of radiation into a range of directions as a result of physical interactions. When a particle intercepts an electromagnetic wave, part of the wave's energy is removed by the particle and re-radiated into a solid angle centered at it. The scattered light is polarized, and of the same wavelength as the incident wavelength, which means that there is no loss of energy to the particle [19].

There are three main types of scattering: (1) Rayleigh scattering, (2) Mie scattering, and (3) non-selective scattering. The scattering effect depends on the characteristic size parameter  $x_0$ , such as that  $x_0 = 2\pi r / \lambda$ , where,  $r$  is the size of the aerosol particle encountered during propagation [24]. If  $x_0 \ll 1$ , the backward lobe becomes larger and the side lobes disappear[25] and the scattering process is termed as Rayleigh scattering. If  $x_0 \approx 1$ , the backward lobe is symmetrical with the forward lobe and then it is Mie scattering. For  $x_0 \gg 1$ , the particle presents a large forward lobe and small side lobes that start to appear and the scattering process is termed as non-selective scattering. It is possible to calculate the scattering coefficients from the concentration of the particles and the effective cross section such as Eq. (4) [2]:

$$\beta_{scat} = \alpha_{scat} N_{scat} [1/km] \tag{4}$$

Where:

$\beta_{scat}$ : is either Rayleigh (molecular)  $\beta_m$  or Mie (aerosols)  $\beta_a$  scattering.

$\alpha_{scat}$ : is a cross-section parameter [ $km^2$ ].

$N_{scat}$ : is a particle concentration [ $1/km^3$ ].

The total scattering can be written as presented in Eq. (5):

$$\beta_{scat} = \beta_m + \beta_a [1/km] \tag{5}$$

### 3.5.1 Rayleigh (molecular) scattering

Rayleigh scattering refers to scattering by molecular and atmospheric gases of sizes much less than the incident light wavelength. The Rayleigh scattering coefficient is given by Eq. (6) [2]:

$$\beta_m = \alpha_m N_m [1/km] \tag{6}$$

Where:

$\alpha_m$ : is the Rayleigh scattering cross-section [ $km^2$ ].

$N_m$ : is the number density of air molecules [ $1/km^3$ ].

Rayleigh scattering cross section is inversely proportional to fourth power of the wavelength of incident beam ( $\lambda^{-4}$ ) as the following relationship:

$$\alpha_m = \frac{8\pi^3(n^2-1)^2}{3N^2\lambda^4} [km^2] \tag{7}$$

Where:

$n$ : is the index of refraction.

$\lambda$ : is the incident light wavelength [ $m$ ].

$N$ : is the volumetric density of the molecules [ $1/km^3$ ].

The result is that Rayleigh scattering is negligible in the infrared waveband because Rayleigh scattering is primarily significant in the ultraviolet to visible wave range [19].

### 3.5.2 Mie (aerosols) scattering

Mie scattering occurs when the particle diameter is equal or larger than one-tenth the incident laser beam wavelength, Mie scattering is the main cause of attenuation at laser wavelength of interest for FSO communication at terrestrial altitude. Transmitted optical beams in free space are attenuated most by the fog and haze droplets mainly due to dominance of Mie scattering effect in the wavelength band of interest in FSO ( $0.5 \mu\text{m} - 2 \mu\text{m}$ ). This makes fog and haze a keys contributor to optical power/irradiance attenuation. The attenuation levels are too high and obviously are not desirable [26].

The attenuation due to Mie scattering can reach values of hundreds of dB/km [27], [24] (with the highest contribution arising from fog). The Mie scattering coefficient expressed as follows, see Eq. (8) [2]:

$$\beta_a = \alpha_a N_a [1/\text{km}] \quad (8)$$

Where:

$\alpha_a$ : is the Mie scattering cross-section [ $\text{km}^2$ ].

$N_a$ : is the number density of air particles [ $1/\text{km}^3$ ].

An aerosol's concentration, composition and dimension distribution vary temporally and spatially varying, so it is difficult to predict attenuation by aerosols. Although their concentration is closely related to the optical visibility, there is no single particle dimension distribution for a given visibility [28]. Due to the fact that the visibility is an easily obtainable parameter, either from airport or weather data, the scattering coefficient  $\beta_a$  can be expressed according to visibility and wavelength by the following expression [5]:

$$\beta_a = \left(\frac{3.91}{V}\right) \left(\frac{0.55\mu}{\lambda}\right)^i \quad (9)$$

Where:

$V$ : is the visibility (Visual Range)[ $\text{km}$ ].

$\lambda$ : is the incident laser beam wavelength [ $\mu\text{m}$ ].

$i$ : is the size distribution of the scattering particles which typically varies from 0.7 to 1.6 corresponding to visibility conditions from poor to excellent.

Where:

$i = 1.6$  for  $V > 50\text{km}$ .

$i = 1.3$  for  $6 \text{ km} \leq V \leq 50 \text{ km}$ .

$i = 0.585 V^{1/3}$  for  $V < 6 \text{ km}$ .

Since we are neglecting the absorption attenuation at wavelength of interest and Rayleigh scattering at terrestrial altitude and according to Eq. (2) and Eq. (5) then:

$$\beta_{\text{scat}} = \beta_a \quad (10)$$

The atmospheric attenuation  $\tau$  is given as:

$$\tau = \exp(-\beta_a L) \tag{11}$$

The atmospheric attenuation in *dB*,  $\tau$  can be calculated as follows:

$$\tau = 4.3429\beta_a L \text{ [dB]} \tag{12}$$

### 3.5.3 RAIN

Rain is formed by water vapor contained in the atmosphere. It consists of water droplets whose form and number are variable in time and space. Their form depends on their size: they are considered as spheres until a radius of 1 mm and beyond that as oblate spheroids: flattened ellipsoids of revolution [5].

#### Rainfall effects on FSO systems

Scattering due to rainfall is called non-selective scattering, this is because the radius of raindrops (100 - 1000  $\mu\text{m}$ ) is significantly larger than the wavelength of typical FSO systems. The laser is able to pass through the raindrop particle, with less scattering effect occurring. The haze particles are very small and stay longer in the atmosphere, but the rain particles are very large and stay shorter in the atmosphere. This is the primary reason that attenuation via rain is less than haze. An interesting point to note is that RF wireless technologies that use frequencies above approximately 10 GHz are adversely impacted by rain and little impacted by fog. This is because of the closer match of RF wavelengths to the radius of raindrops, both being larger than the moisture droplets in fog [4]. The rain scattering coefficient can be calculated using Stroke Law see Eq. (13) [29]:

$$\beta_{\text{rainscat}} = \pi a^2 N_a Q_{\text{scat}} \left(\frac{a}{\lambda}\right) \tag{13}$$

Where:

$a$ : is the radius of raindrop, (*cm*).

$N_a$ : is the rain drop distribution, ( $\text{cm}^{-3}$ ).

$Q_{\text{scat}}$ : is the scattering efficiency.

The raindrop distribution  $N_a$  can be calculated using equation following:

$$N_a = \frac{R}{1.33(\pi a^3) V_a} \tag{14}$$

Where:

$R$ : is the rainfall rate (*cm/s*),

$V_a$ : is the limit speed precipitation.

Limiting speed of raindrop [29] is also given as:

$$V_a = \frac{2a^2 \rho g}{9\eta} \tag{15}$$

Where:

$\rho$ : is water density, ( $\rho = 1 \text{ g/cm}^3$ ).

$g$ : is gravitational constant,  $g = 980 \text{ cm/sec}^2$ .

$\eta$ : is viscosity of air,  $\eta = 1.8 * 10^{-4} \text{ g/cm.sec}$ .

The rain attenuation can be calculated by using Beer's law as:

$$\tau = \exp(-\beta_{\text{rainscat}}L) \quad (16)$$

### 3.6 Turbulence

Clear air turbulence phenomena affect the propagation of optical beam by both spatial and temporal random fluctuations of refractive index due to temperature, pressure, and wind variations along the optical propagation path [30][31]. Atmospheric turbulence primary causes phase shifts of the propagating optical signals resulting in distortions in the wave front. These distortions, referred to as optical aberrations, also cause intensity distortions, referred to as scintillation. Moisture, aerosols, temperature and pressure changes produce refractive index variations in the air by causing random variations in density [32]. These variations are referred to as eddies and have a lens effect on light passing through them. When a plane wave passes through these eddies, parts of it are refracted randomly causing a distorted wave front with the combined effects of variation of intensity across the wave front and warping of the isophase surface [33]. The refractive index can be described by the following relationship [34]:

$$n - 1 \approx 79 \times \frac{P}{T} \quad (17)$$

Where:

$P$ : is the atmospheric pressure in [mbar].

$T$ : is the temperature in Kelvin [K].

If the size of the turbulence eddies are larger than the beam diameter, the whole laser beam bends, as shown in Fig. 4. If the sizes of the turbulence eddies are smaller than the beam diameter and so the laser beam bends, they become distorted. Small variations in the arrival time of various components of the beam wave front produce constructive and destructive interference and result in temporal fluctuations in the laser beam intensity at the receiver.

#### 3.6.1 Refractive index structure

Refractive index structure parameter  $C_n^2$  is the most significant parameter that determines the turbulence strength. Clearly,  $C_n^2$  depends on the geographical location, altitude, and time of day. Close to ground, there is the largest gradient of temperature associated with the largest values of atmospheric pressure (and air density). Therefore, one should expect larger values  $C_n^2$  at sea level. As the altitude increases, the temperature gradient decreases and so the air density with the result of smaller values of  $C_n^2$  [3].

In applications that envision a horizontal path even over a reasonably long distance, one can assume  $C_n^2$  to be practically constant. Typical value of  $C_n^2$  for a weak turbulence at ground level can be as little as  $10^{-17} \text{ m}^{-2/3}$ , while for a strong turbulence it can be up to  $10^{-13} \text{ m}^{-2/3}$  or

larger. However, a number of parametric models have been formulated to describe the  $C_n^2$  profile and among those, one of the more used models is the Hufnagel-Valley [35] given by Eq. (18):

$$C_n^2(h) = 0.00594(v/27)^2 (10^{-5}h)^{10} \exp(-h/1000) + 2.7 \times 10^{-16} \exp(-\frac{h}{1500}) + A_o \exp(-\frac{h}{100}) \quad (18)$$

Where:

$h$ : is the altitude in [m].

$v$ : is the wind speed at high altitude [m/s].

$A_o$ : is the turbulence strength at the ground level,  $A_o = 1.7 \times 10^{-14} \text{m}^{-2/3}$ .

The most important variable in its change is the wind and altitude. Turbulence has three main effects [36]; scintillation, beam wander and beam spreading.

### 3.6.2 Scintillation

Scintillation may be the most noticeable one for FSO systems [9]. Light traveling through scintillation will experience intensity fluctuations, even over relatively short propagation paths. The scintillation index,  $\sigma_i^2$  describes such intensity fluctuation as the normalized variance of the intensity fluctuations given by Eq. (19) [3]:

$$\sigma_i^2 = \frac{\langle(I-\langle I \rangle)^2\rangle}{\langle I \rangle^2} = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1 \quad (19)$$

Where:

$I = |E|^2$ : is the signal irradiance (or intensity).

The strength of scintillation can be measured in terms of the variance of the beam amplitude or irradiance  $\sigma_i$  given by the following:

$$\sigma_i^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \quad (20)$$

Here,  $k = 2\pi/\lambda$  is the wave number and this expression suggests that longer wavelengths experience a smaller variance.

Where the Eq. (20) is valid for the condition of weak turbulence mathematically corresponding to  $\sigma_i^2 < 1$ . Expressions of lognormal field amplitude variance depend on: the nature of the electromagnetic wave traveling in the turbulence and on the link geometry [3].

### 3.6.3 Beam spreading

Beam spreading describes the broadening of the beam size at a target beyond the expected limit due to diffraction as the beam propagates in the turbulent atmosphere. Here, we describe the case of beam spreading for a Gaussian beam, at a distance  $L$  from the source, when the turbulence is present. Then one can write the irradiance of the beam averaged in time as presented in Eq. (21) [36]:

$$I(l, r) = \frac{2P_o}{\pi\omega_{eff}^2(l)} \exp\left(\frac{-2r^2}{\omega_{eff}^2(l)}\right) \quad (21)$$

Where:

$P_o$ : is total beam power in W.

$r$ : is the radial distance from the beam center.

The beam will experience a degradation in quality with a consequence that the average beam waist in time will be  $\omega_{eff}(l) > \omega(l)$ . To quantify the amount of beam spreading, describes the effective beam waist average as:

$$\omega_{eff}(l)^2 = \omega(l)^2(1 + T) \quad (22)$$

Where:

$\omega(l)$ : is the beam waist that after propagation distance  $L$  is given by:

$$\omega(l)^2 = \left[ \omega_o^2 + \left( \frac{2L}{k\omega_o} \right)^2 \right] \quad (m^2) \quad (23)$$

In which  $\omega_o$  is the initial beam waist at  $L = 0$ ,  $T$ : is the additional spreading of the beam caused by the turbulence. As seen in other turbulence figure of merits,  $T$  depends on the strength of turbulence and beam path. Particularly,  $T$  for horizontal path, one gets [37]:

$$T = 1.33\sigma_t^2 \Lambda^{5/6} \quad (24)$$

While the parameter  $\Lambda$  is given by:

$$\Lambda = \frac{2L}{k\omega^2(l)} \quad (25)$$

The effective waist,  $\omega_{eff}(l)$ , describes the variation of the beam irradiance averaged over long term.

As seen in other turbulence figure of merits,  $\omega_{eff}(l)^2$  depends on the turbulence strength and beam path [37]. Evidently, due to the fact that  $\omega_{eff}(l) > \omega(l)$  beam will experience a loss that at beam center will be equal:

$$L_{BE} = 20 \log_{10}(\omega(l)/\omega_{eff}(l)) \text{ (dB)} \quad (26)$$

### 3.7 Total attenuation

Atmospheric attenuation of FSO system is typically dominated by haze, fog and is also dependent on rain. The total attenuation is a combination of atmospheric attenuation in the atmosphere and geometric loss.

Total attenuation for FSO system is actually very simple at a high level (leaving out optical efficiencies, detector noises, etc.). The total attenuation is given by the following [38]:

$$\frac{P_r}{P_t} = \frac{d_s^2}{(d_s + (\theta L))^2} \times \exp(-\beta L) \quad (27)$$

Where:

$P_t$ : is the transmitted power [mw].

$P_r$ : is the received power [mw].

$\theta$ : is the beam divergence [mrad].

$\beta$ : is the total scattering coefficient [1/km].

Looking at this equation, the variables that can be controlled are the aperture size, the beam divergence and the link range. The scattering coefficient is uncontrollable in an outdoor environment. In real atmospheric situations, for availabilities at 99.9% or better, the system designer can choose to use huge transmitter laser powers, design large receiver apertures, design small transmitter apertures and employ small beam divergence. Another variable that can be controlled is link range, which must be of a short distance to ensure that the atmospheric attenuation is not the dominant term in the total attenuation [14].

### 3.8 Conclusion

FSO communication systems are affected by atmospheric attenuation that limits their performance and reliability. The atmospheric attenuation by fog, haze, rainfall, and scintillation has a harmful effect on FSO system. The majority of the scattering occurred to the laser beam is due to the Mie scattering. This scattering is due to the fog and haze aerosols existed at the atmosphere. This scattering is calculated through visibility. FSO attenuation at thick fog can reach values of hundreds dB. Thick fog reduces the visibility range to less than 50 m, and it can affect on the performance of FSO link for distances as small. The rain scattering (non-selective scattering) is wavelength independent and it does not introduce a significant attenuation in wireless IR links, it affect mainly on microwave and radio systems that transmit energy at longer wavelengths.

There are three effects on turbulence: scintillation, laser beam spreading and laser beam wander. Scintillation is due to variation in the refractive index structure of air, so if the light travelling through scintillation, it will experience intensity fluctuations. The Geometric loss depends on FSO components design such as beam divergence, aperture diameter of both transmitter and receiver. The total attenuation depends on atmospheric attenuation and Geometric loss. In order to reduce total attenuation, FSO system must be designed so that the effect of geometric loss and atmospheric attenuation is small.

## 4. Simulation results and analysis

FSO system used the laser beam to transfer data through atmosphere. The bad atmospheric conditions have harmful effects on the transmission performance of FSO. These effects could result in a transmission with insufficient quality and failure in communication. So, the implementation of the FSO requires the study of the local weather conditions patterns. Studying of the local weather conditions patterns help us to determine the atmospheric attenuation effects on FSO communication that occurs to laser beam at this area. In this part of this work, we shall discuss the effects of atmospheric attenuation, scattering coefficient during rainy and hazy days and atmospheric turbulence during clear days on the FSO system performance. Finally, we will calculate the atmospheric turbulence.

In this part we refer to the discussion and analysis of the effects of atmospheric attenuation, scattering coefficient and atmospheric turbulence on FSO system at weather conditions in the Republic of Yemen.

Results analysis is based on weather conditions data in Yemen which has been obtained from the (CAMA) for visibility are listed in Table (4) for the year 2008 and for wind velocity are listed in Table (10) for year 2003. The data of rainfall rate obtained from the (PAWR) are listed in Table (4) for the year 2008. Real data has been included in this analysis. Data has been collected and classified into two types:

1. Hazy days' data: which has been classified based on low and average visibility.
2. Rainy days' data: has been classified based on the rainfall rate at heavy, moderate and light rainfall.
3. Clear days' data: has been classified based on wind velocity.

Based on the above classification we have calculated the following:

1. Scattering coefficient at hazy and rainy days.
2. Atmospheric and total attenuation at hazy and rainy days and link range.
3. Effects of turbulence based on the wind velocity.

Visibility in km		Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
		Sana'a	Av.	9.9	8	9.1	9.1	9.5	7.3	5.6	8.6	9.8	9.8	10
Low	5		0.3	1	2	4	0.7	0.5	2	3	2	7	6	
Aden	Av.	9.7	8.3	9.1	9.2	9.4	7	5.7	8	9.1	9.2	9.8	9.7	
	Low	6	2	5	7	3	3	1	5	3	0.05	8	7	
Taiz	Av.	9	8.4	9.7	9.7	9.9	8.9	8	8.8	9.9	9.5	9.3	8.9	
	Low	0.05	0.05	4	4	0.05	2	3	1.5	1	1.5	0.1	0.1	

Table 4. The Data of Visibility (km) obtained from CAMA for Year 2008.

#### 4.1 Scattering coefficient in hazy days

In this part we shall discuss and analyze the effects of scattering coefficient on the FSO system performance during hazy days for Yemen and cities of Sana'a, Aden and Taiz. We will discuss and analyze the scattering coefficient during hazy days at low and average visibility. We will calculate the values of scattering coefficient using the Eq. 4.9 assuming that the size of distribution of scattering particles for low visibility is  $i = 0.585V^{1/3}$  and for average visibility is  $i = 1.3$ . The range of low visibility extends from 0.8 km to 5 km and the range of average visibility extends from 6.4 km to 5 km as shown in the Table (8).

Figure (5) represents the performance of scattering coefficient versus low visibility at wavelengths 780 nm, 850 nm and 1550 nm. This figure shows that the scattering coefficient inversely proportions with visibility. Scattering coefficient at low visibility 0.8 km is 4 km<sup>-1</sup>, 3.9 km<sup>-1</sup> and 2.8 km<sup>-1</sup> for wavelengths 780 nm, 850 nm and 1550 nm respectively. The scattering coefficient of 5 km low visibility is 0.55 km<sup>-1</sup>, 0.51 km<sup>-1</sup> and 0.28 km<sup>-1</sup> for wavelengths 780 nm, 850 nm, and 1550 nm respectively.

Figure (6) illustrates the scattering coefficient performance versus average visibility. When visibility is 6.4 km, scattering coefficient obtained was 0.39 km<sup>-1</sup>, 0.35 km<sup>-1</sup> and 0.16 km<sup>-1</sup> for wavelengths 780 nm, 850 nm and 1550 nm respectively while at 9.7 km visibility it was 0.26 km<sup>-1</sup>, 0.23 km<sup>-1</sup> and 0.11 km<sup>-1</sup> for wavelengths 780 nm, 850 nm, and 1550 nm respectively.

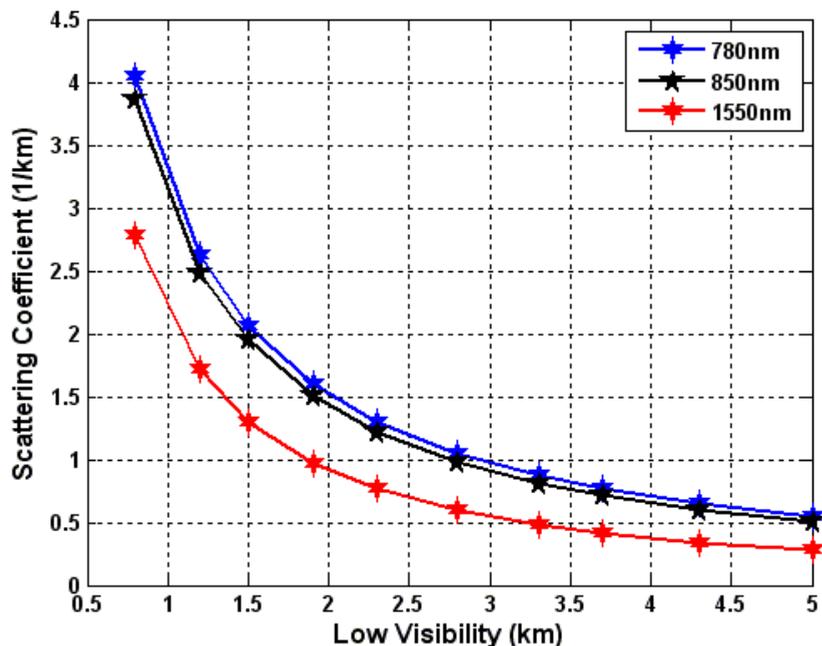


Fig. 5. Scattering Coefficient (km<sup>-1</sup>) versus Low Visibility (km).

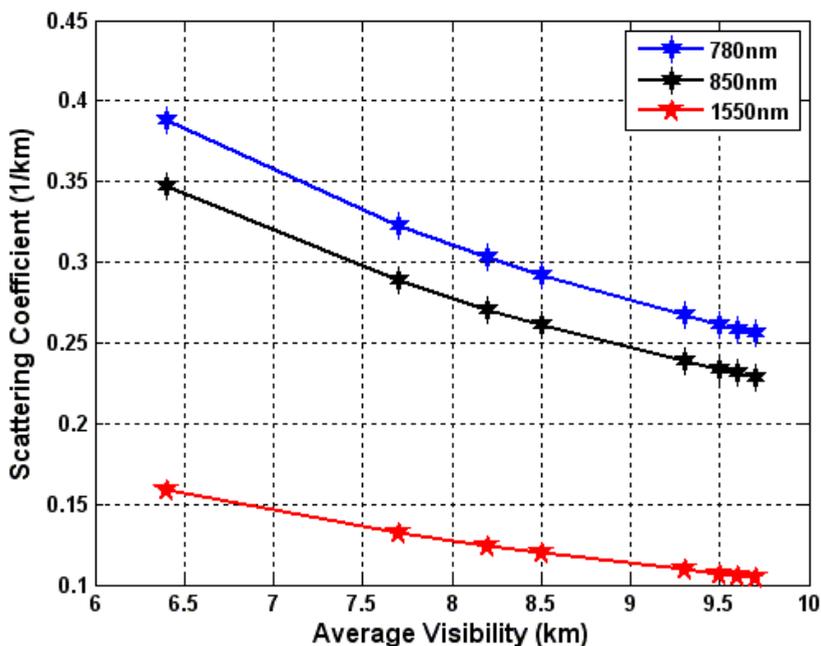


Fig. 6. Scattering Coefficient ( $\text{km}^{-1}$ ) versus Average Visibility (km).

These results show that the wavelength 1550 nm is scattered less than wavelengths 850 nm and 780 nm. The scattering affects are less in average visibility compared with low visibility. This is because the distribution of particles density at low visibility is higher than the density of particles at average visibility. The results of scattering coefficient due to hazy days are given in the Table (5).

Visibility	Wavelength	From	To
		Scattering ( $\text{km}^{-1}$ )	Scattering ( $\text{km}^{-1}$ )
Low	780 nm	4	0.55
	850 nm	3.9	0.51
	1550 nm	2.8	0.28
Average	780 nm	0.39	0.26
	850 nm	0.35	0.23
	1550 nm	0.16	0.11

Table 5. The Results of Scattering Coefficient due to Hazy Days.

#### 4.2 Atmospheric attenuation in hazy days

In this part we will discuss and analyze the effects of atmospheric attenuation on the FSO system performance during hazy days. We have obtained the value of atmospheric attenuation from Eq. (12) assuming that the distance between transmitter and receiver is 1 km.

Figure (7) shows that the atmospheric attenuation inversely proportions with visibility. When the visibility is higher the effect of atmospheric attenuation is higher too. At low visibility of 0.8 km, atmospheric attenuation is 17.6 dB, 16.8 dB and 12.1 dB for wavelengths 780 nm, 850 nm and 1550 nm respectively. For 5 km low visibility, the atmospheric attenuation is about 2.4 dB, 2.2 dB and 1.2 dB for wavelengths 780 nm, 850 nm and 1550 nm respectively.

Figure (8) represents the atmospheric attenuation versus average visibility. When visibility is 6.4 km, atmospheric attenuation is 1.7 dB, 1.5 dB and 0.69 dB for wavelengths 780 nm, 850 nm and 1550 nm respectively. For a 9.7 km visibility, the atmospheric attenuation is 1.1 dB, 0.99 dB and 0.46 dB for wavelengths 780 nm, 850 nm and 1550 nm respectively.

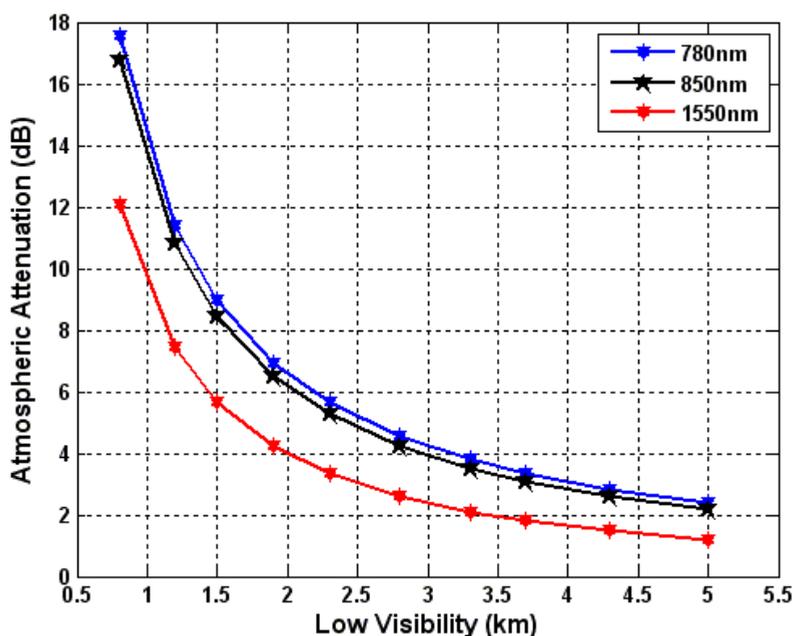


Fig. 7. Atmospheric Attenuation (dB) versus Low Visibility (km).

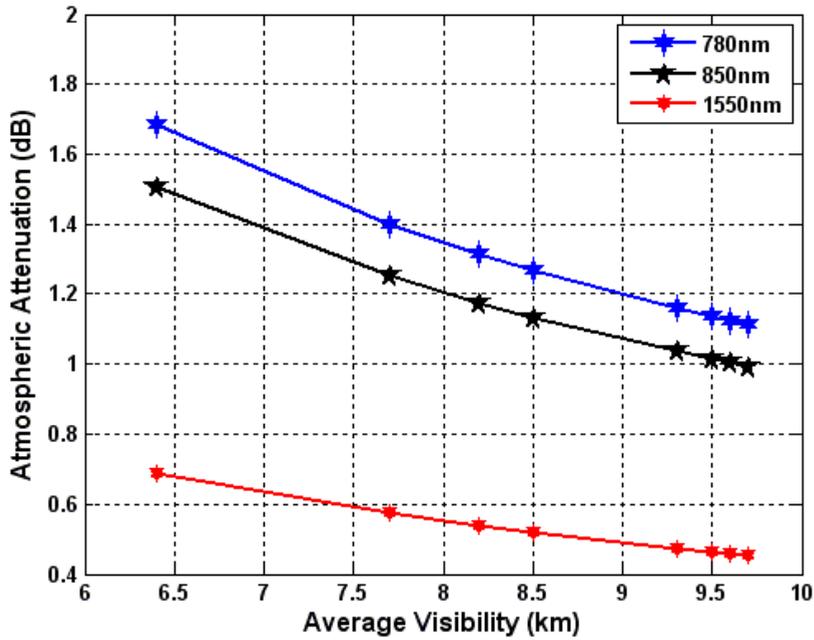


Fig. 8. Atmospheric Attenuation (dB) versus Average Visibility (km).

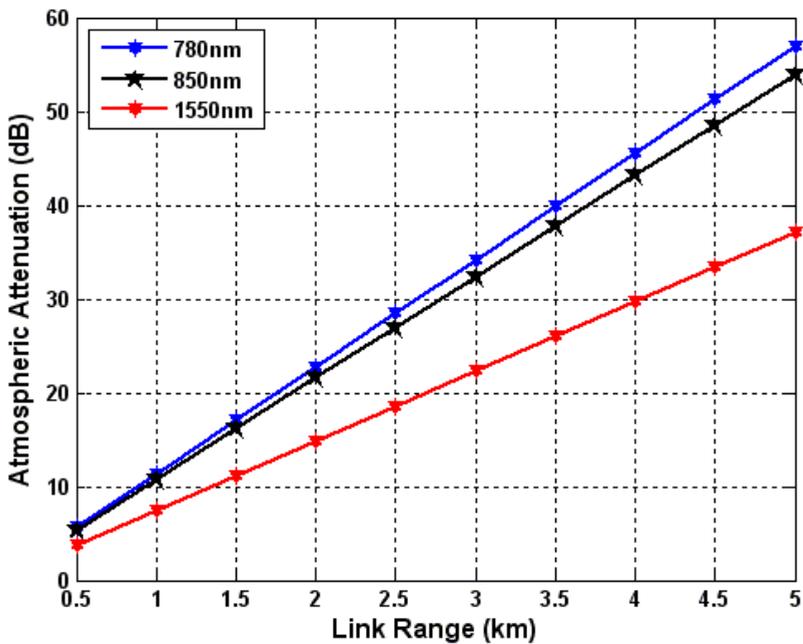


Fig. 9. Atmospheric Attenuation (dB) versus Link Range (km).

Figure (9) indicates to the atmospheric attenuation versus link range that extends from 0.5 km to 5 km. Here we assume that the visibility is 1.2 km and  $i = 0.585 * v^{1/3}$ . The more the distance between the transmitter and the receiver, the more the atmospheric attenuation is. This means that when the distance between the transmitter and the receiver increases, it is able to reduce the quality of transmission and effectiveness of FSO system. Atmospheric attenuation for link range 0.5 km at low visibility is 5.7 dB, 4.5 dB, 3.7 dB for wavelengths 780 nm, 850 nm and 1550 nm respectively. When the link range was about 5 km, atmospheric attenuation was 56.9 dB, 54 dB and 37.2 dB, for wavelengths 780 nm, 850 nm and 1550 nm respectively.

These results show that the attenuation at low visibility is higher than attenuation at average visibility. In addition, these readings have proved that the wavelength 1550 nm is capable to reduce the effect of atmospheric attenuation on FSO system. The distance between transmitter and receiver at low visibility should be reduced to avoid the effect of atmospheric attenuation on FSO system and improve its performance. The results of atmospheric attenuation due to hazy days are given in the Table (6).

Visibility	Wavelength	From	To
		Attenuation (dB)	Attenuation (dB)
Low	780 nm	17.6	2.4
	850 nm	16.8	2.2
	1550 nm	12.1	1.2
Average	780 nm	1.7	1.1
	850 nm	1.5	0.99
	1550 nm	0.69	0.46

Table 6. The Results of Atmospheric Attenuation due to Hazy Days.

### 4.3 Scattering coefficient in rainy days

Figures below were plotted based on Eq. (14) assuming the water density ( $\rho = 0.001 \text{ g/mm}^3$ ), gravitational constant ( $g = 127008 * 10^6 \text{ mm/hr}^2$ ), viscosity of air ( $\eta = 0.0648 \text{ g/mm.hr}$ ) and scattering efficiency ( $Q = 2$ ). The data of rainfall rate which listed in the Table (7) are divided into three states: light, moderate and heavy rain.

Rainfall rate (mm/hr)	Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
	Sana'a	2.7	2.6	2.1	1	0	0	2.3	3	0	0	1	0.6
Aden	0	0	0	1	0.5	0	0	1.2	0	0	0	0	
Taiz	2.4	0.5	3.75	5.77	5.41	3.1	5	4.72	4.02	2.4	1.5	0.5	

Table 7. The Data of Rainfall Rate (mm/hr) obtained from (PAWR) for Year 2008.

Figure (10) illustrates the performance of scattering coefficients versus rainfall rate at light, moderate and heavy rain. The curves plotted were based on Eq. (14) assuming the radius of raindrop = 0.5 mm. The scattering coefficient is proportional with rainfall rate, which showed that when the rainfall rate increases, the scattering coefficient increases too. For light rain the scattering coefficient is about  $0.008 \text{ km}^{-1}$  to  $0.04 \text{ km}^{-1}$ , about  $0.055 \text{ km}^{-1}$  to  $0.086 \text{ km}^{-1}$  for moderate rain and  $0.10 \text{ km}^{-1}$  to  $0.16 \text{ km}^{-1}$  for heavy rain. The highest scattering coefficient is about  $0.16 \text{ km}^{-1}$  in heavy rain. The impact of scattering on transmission of FSO system is more pronounced during heavy rainfall compared to moderate and light rainfall.

Figure (11) shows that the scattering coefficient versus raindrop radius. This figure illustrated that the radius of raindrop was important in evaluating the scattering effect. The radii of raindrop fall in the range of 0.1 mm to 0.8 mm. The scattering coefficient of the rain is independent of wavelength because the radii of rain particles are much bigger than laser wavelengths.

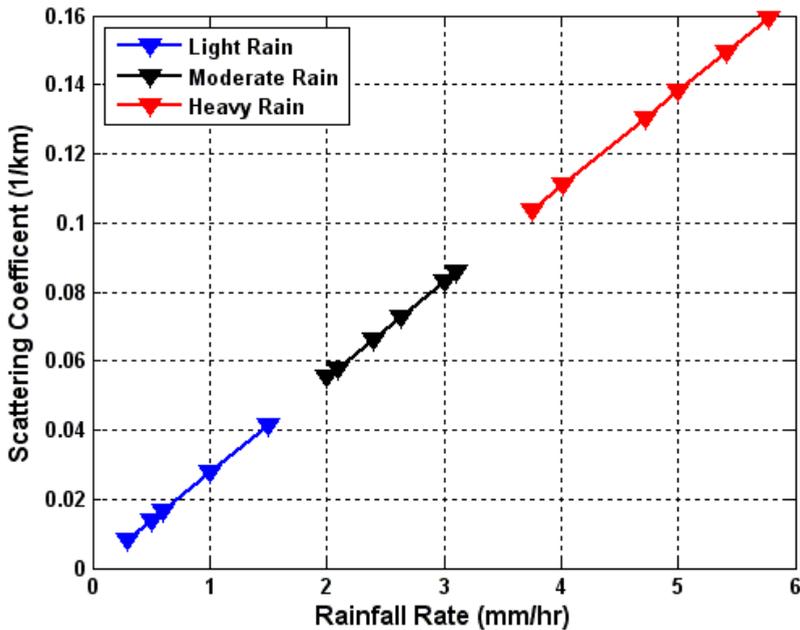


Fig. 10. Scattering Coefficient ( $\text{km}^{-1}$ ) versus Rainfall Rate ( $\text{mm/hr}$ ).

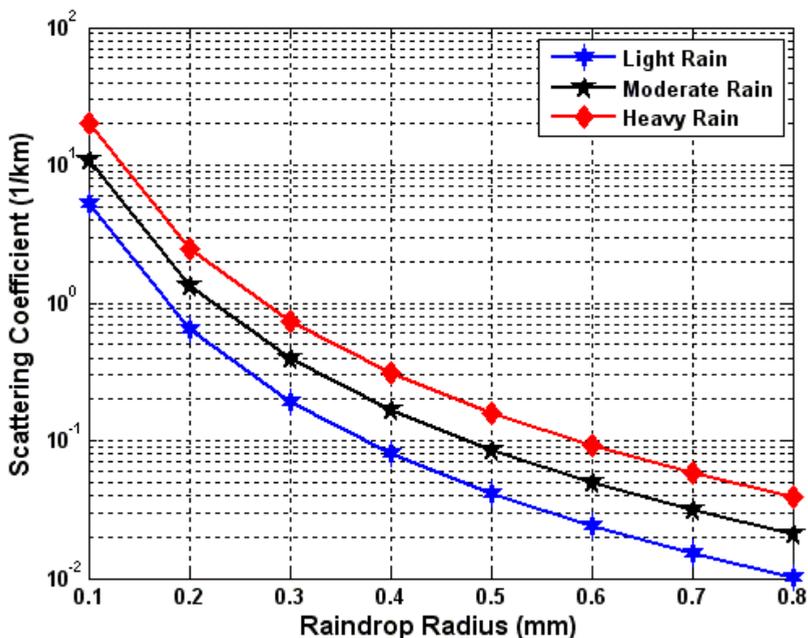


Fig. 11. Scattering Coefficient ( $\text{km}^{-1}$ ) versus Raindrop Radius (mm).

The results of scattering coefficient due to rainy days are given in the Table (8).

Rainfall rate	From	To
	Scattering ( $\text{km}^{-1}$ )	Scattering ( $\text{km}^{-1}$ )
Light rain	0.0083	0.041
Moderate rain	0.055	0.086
Heavy rain	0.10	0.16

Table 8. The Results of Scattering Coefficient due to Rainy Days.

#### 4.4 Atmospheric attenuation in rainy days

In this part we will discuss the effects of atmospheric attenuation on the performance of FSO system during rainy days. The effects of atmospheric attenuation on FSO systems during rainy days depended on rainfall rate intensity and raindrop radius.

Figure (12) shows the atmospheric attenuation versus rainfall rate. The curves plotted were based on Eq. 17 at light, moderate and heavy rain, assuming the radius of rain  $a = 0.5$  mm and transmission range  $L = 1$  km. When the rainfall rate increases the effect of atmospheric attenuation on the FSO system increases too. Therefore influence of attenuation on transmission of FSO systems is more prominent during heavy rainfall compared to moderate and light rainfall. The atmospheric attenuation is about 0.036 dB to 0.18 dB for light rain, about 0.24 dB to 0.37 dB for moderate rain and 0.45 dB to 0.69 dB for heavy rain. The highest attenuation is about 0.69 dB in heavy rain.

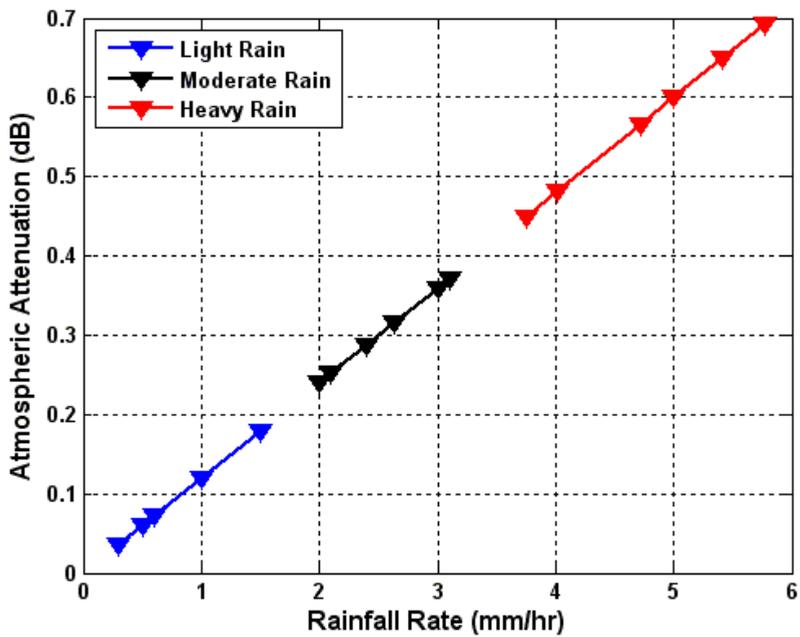


Fig. 12. Atmospheric Attenuation (dB) versus Rainfall Rate (mm/hr).

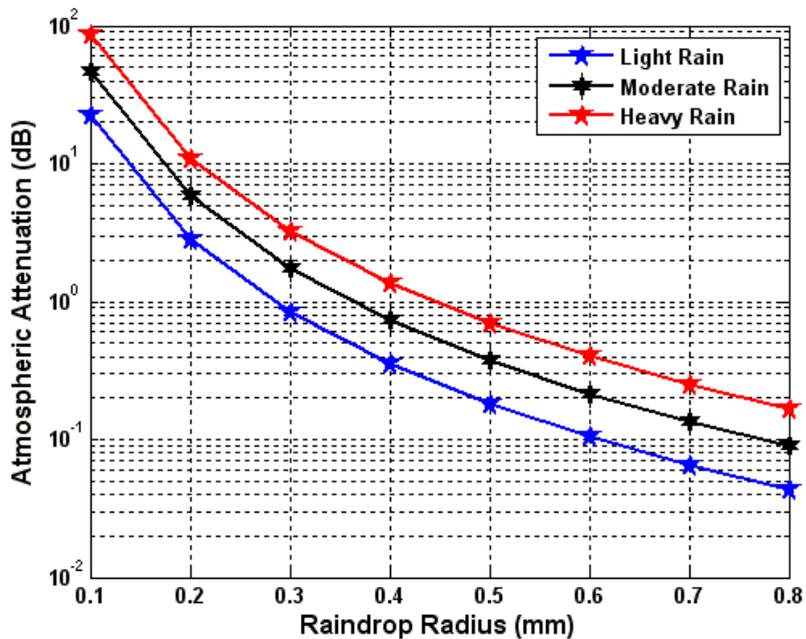


Fig. 13. Atmospheric Attenuation (dB) versus Raindrop Radius (mm).

Figure (13) illustrates that the atmospheric attenuation versus raindrop radius. The radius of rain particles falls in the range of 0.1 mm to 0.8 mm. This figure shows that the atmospheric attenuation decreases when the radius of raindrop increases.

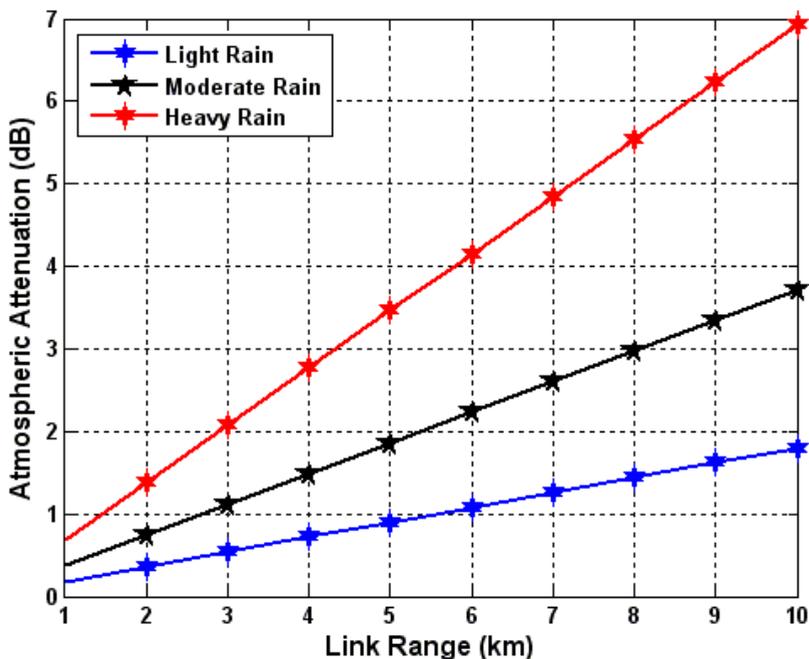


Fig. 14. Atmospheric Attenuation (dB) versus Link Range (km).

Figure (14) indicates the atmospheric attenuation versus link range. This figure was plotted based on Eq. (17) assuming the raindrop radius is 0.5 mm. For 0.5 km link range the atmospheric attenuation is about 0.18 dB for light rain, 0.37 dB for moderate rain and 0.69 dB for heavy rain. For 10 km link range the atmospheric attenuation is about 1.8 dB for light rain, 3.7 dB for moderate rain and 6.9 dB for heavy rain. The atmospheric attenuation results due to rainy days are given in the Table (9).

Rainfall rate	Atmospheric Attenuation (dB)	
	From	To
Light rain	0.036	0.18
Moderate rain	0.24	0.37
Heavy rain	0.45	0.69

Table 9. The Results of Atmospheric Attenuation due to Rainy Days.

#### 4.5 Atmospheric turbulence

The purpose here is to discuss the relationship for calculating irradiance variance, beam spreading and loss beam center for a range of parameters. We used the wavelengths of 780 nm, 850 nm & 1550 nm.

Wind Velocity(km\hr)	Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
	Sana'a	15.6	17.4	15.2	15.2	14.8	16.1	17.6	16.5	18.9	16.9	16.3	14.8
Aden	20.6	18.5	20.9	20	13.3	18.3	21.3	20.6	14.6	16.7	20	19.1	
Taiz	12.4	14.6	16.1	17.2	17	18.3	21.7	17	17	14.8	14.4	13	

Table 10. The Data of Wind Velocity (km/hr) obtained from (CAMA) for Year 2003.

Figure (15) illustrates the log irradiance variance versus the link range for 780 nm, 850 nm and 1550 nm wavelengths. This figure was plotted based on Eq. 21. As the link range increases the variance (scintillation) increases too. For a 0.5 km link range, the variance is about 0.087, 0.079 and 0.039 for wavelengths 780 nm, 850 nm and 1550 nm respectively. For a 5 km link range, the variance is about 5.9, 5.4 and 2.7 for 780 nm, 850 nm and 1550 nm respectively. These results show that the use of a wavelength of 1550 nm is able to reduce the variance "atmospheric turbulence" effect on the FSO systems.

Figure (16) indicates the comparison between the beam spreading on a distance (L) from the transmitter, in case the atmospheric turbulences and its absence. Figure (15) was plotted based on Eq. 23 assuming the spot size of the beam at the transmitter (with the distance  $L = 0$ ) equals 8 mm. At the distance 0.5 km from transmitter, the spot size of the beam is  $\omega(l) = 0.032$  m in case of absence turbulences and  $\omega_{eff}(l) = 0.032$  m in case of turbulences. At the distance 5 km, the  $\omega(l) = 0.31$  m and  $\omega_{eff}(l) = 0.33$  m. From the above results, we conclude the expansion of the spot size of the beam depends on the distance between transmitter and receiver and on the atmospheric turbulence on the along of transmission range.

The loss beam at center (dB) depends on transmission range and wavelength as shown Fig. (17). The loss beam at the center increases, corresponding to the increase of Link range. At the distance 0.5 km, the loss beam at center = 0.0454 dB, 0.0383 dB and 0.0116 dB for wavelengths 780 nm, 850 nm & 1550 nm respectively. At the distance 5 km, the loss beam at center is 2.4 dB, 2.1 dB and 0.72 dB for wavelengths 780 nm, 850 nm & 1550 nm respectively.

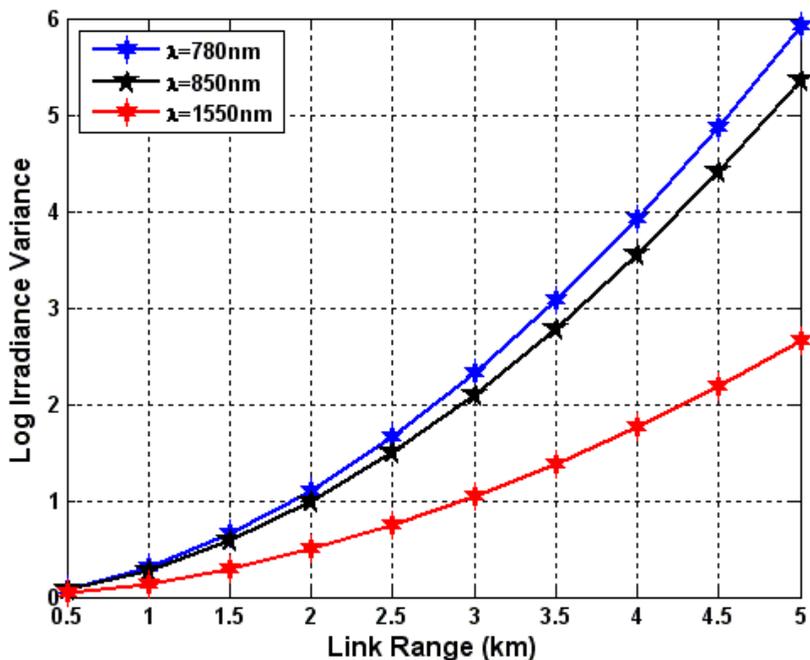


Fig. 15. Log Irradiance Variance Scintillation versus Link Range (km).

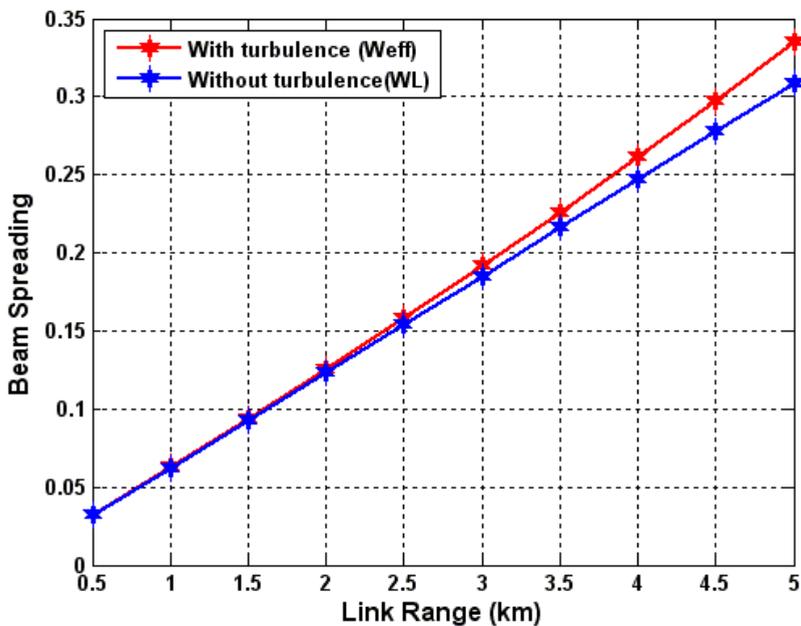


Fig. 16. Beam Spreading (m) versus the Link Range (km).

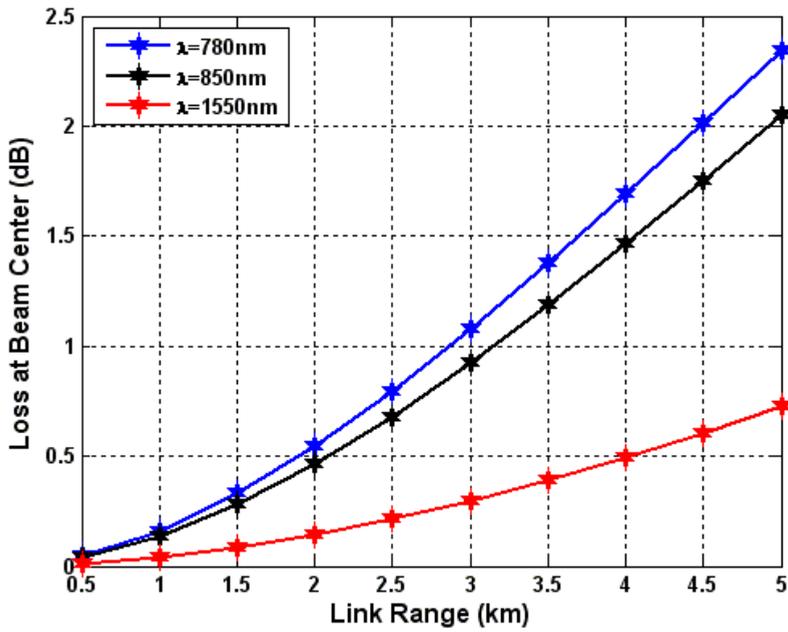


Fig. 17. Loss at Beam Center (dB) versus the Link Range (km).

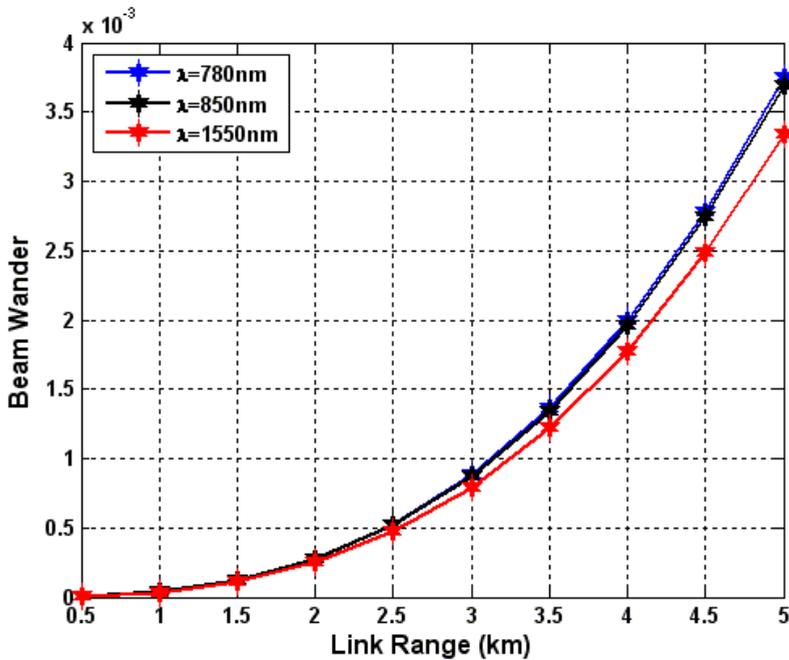


Fig. 18. Beam Wander (m) versus the Link Range (km).

Figure (18) indicates to the beam wander versus link range. The beam wanders increases corresponding to increasing in the link range. At 0.5 km transmission range, the beam wander is 0 m for 780 nm, 850 nm and 1550nm wavelengths respectively and at 5 kmlink range the beam wander is 0.0037 m, 0.0037 m, and 0.0033 m for 780 nm, 850nm and 1550 nm wavelengths respectively. From the above results, we conclude that the loss beam at center for 780 nm and 850 nm wavelengths is more than the loss at 1550nm wavelength. So to reduce the loss beam at center we suggest to reduce the link range and 1550 nm wavelength must be used. The results of atmospheric turbulence effect due to clear days are given in the Table (11).

Link Range (km)	Wavelength	Scintillation ( $m^{-3/2}$ )	Loss at Beam center (dB)	Beam wander (m)	W (L) (m)	$W_{eff}$ (L) (m)
0.5 km	780 nm	0.087	0.045	0.0	0.032	0.032
	850 nm	0.076	0.038	0.0		
	1550 nm	0.039	0.012	0.0		
5 km	780 nm	5.92	2.35	0.0037	0.31	0.33
	850 nm	5.35	2.050	0.0037		
	1550 nm	2.66	0.73	0.0033		

Table 11. The Results of Atmospheric Turbulence due to Clear Days.

#### 4.6 Conclusion

In this chapter, we focused on haze, rain and turbulence effects on FSO systems. Mie scattering occurs in hazy days and it depends on wavelength. The scattering coefficient on hazy days is determined by using Beer’s Law. From the results analysis and data in the Table 5.1 the fog and haze represent the most important atmospheric scatters. Their attenuation, which can reach about 17.6 dB at 1.8 km low visibility in Yemen and 163.5 dB (corresponding to very thick fog), at 0.05 km low visibility is in Taiz city. This attenuation value affects the performance of a FSO link for distances as small. Wavelength 1550 nm is less scattered from the wavelengths 850 nm & 780 nm and it is not harmful to the human eyes.

Rain does not introduce a significant attenuation in FSO systems links in Yemen. This is due to the rainfall affect mainly radio and microwave systems that use a longer wavelengths and attenuation at heavy rain 5.77 mm/hr in Yemen about 0.69 dB, is very small compared with attenuation due to fog. Therefore the effect of rain is neglected in Yemen. Atmospheric turbulence will change in refractive index structure of air from one area to another. Atmospheric turbulence fluctuates intensity of the laser beam. Scintillation is wavelength and distance dependent. We can reduce the effect of the turbulence by enlarging the diameter of the receiver's aperture or setting tracking system at the receiver. The results indicate that the attenuation depends on weather conditions which are uncontrollable and transmission range which can be controlled; hence, it is considered an important element in the design of FSO system. So, to improve the performance of FSO system, we must reduce the transmission range and use wavelength 1550 nm.

## 5. General conclusion of this chapter

FSO system can spread as a reliable solution for high bandwidth and short distance. There are some factors which must be taken into consideration during the design of FSO system as controllable and uncontrollable factors. Controllable factors include wavelength, transmission range, beam divergence, loss occurred between transmitter and receiver and detector sensitivity. Uncontrollable factors include visibility, rainfall rate, raindrop radius, atmospheric attenuation and scintillation.

Atmospheric attenuation may be absorption or scattering. Absorption lines at the visible and IR wavelengths are narrow and separated. So, we can ignore absorption effect at the wavelength identified as atmospheric windows. Wavelength at FSO system must be eye safe and able to transmit a sufficient power during the bad weather condition. Mie scattering represents the main affects on FSO systems. The main cause of Mie scattering is fog and hazy. Attenuation caused by fog in Yemen is so important for Taiz as the low visibility range can less than 0.05 km during the extensive fog according to the data taken from metrology authority. Transmission in this city may be cut off, so the distance between the transmitter and receiver must be reduced. However, Sana'a and Aden cities the weather is clear during the whole year in comparison with Taiz city. Rayleigh scattering we can ignore it at the visible and infrared wavelength as its effect on the ultraviolet wavelengths is huge. This scattering occurs when the molecules size is less than the wave length of the laser beam.

Non-selective scattering independent on wavelength and occurs when the molecules size is bigger than wavelength and it occurs due to the rainfall. Generally, FSO system is so adequate in Yemeni environment according to the previous results. The performance of wavelength 1550 nm is better at the bad weather conditions in comparison with wavelengths 850 nm and 780 nm. Furthermore, the wavelength 1550 nm allows a high power may reach to over 50 times in comparison with the wavelengths 850 nm & 780 nm.

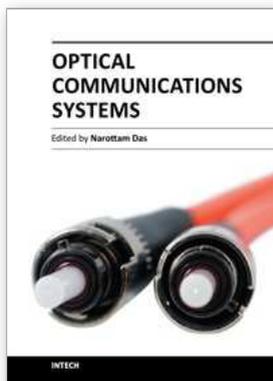
By analyzing results obtained at chapter four, we conclude that we are able to improve the performance of transmission of FSO system at the bad weather conditions by using the wavelength 1550 nm and short distance between transmitter and receiver.

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## **Optical Communications Systems**

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Optical communications systems are very important for all types of telecommunications and networks. They consist of a transmitter that encodes a message into an optical signal, a channel that carries the signal to its destination, and a receiver that reproduces the message from the received optical signal. This book presents up to date results on communication systems, along with the explanations of their relevance, from leading researchers in this field. Its chapters cover general concepts of optical and wireless optical communication systems, optical amplifiers and networks, optical multiplexing and demultiplexing for optical communication systems, and network traffic engineering. Recently, wavelength conversion and other enhanced signal processing functions are also considered in depth for optical communications systems. The researcher has also concentrated on wavelength conversion, switching, demultiplexing in the time domain and other enhanced functions for optical communications systems. This book is targeted at research, development and design engineers from the teams in manufacturing industry; academia and telecommunications service operators/providers.

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