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Chapter 5

Free Space Optical Communications — Theory and Practices

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1. Introduction

1.1. FSO concepts

1.1.1. What is Free Space Optics (FSO)?

FSO is a line-of-sight technology that uses lasers to provide optical bandwidth connections or FSO is an optical communication technique that propagate the light in free space means air, outer space, vacuum, or something similar to wirelessly transmit data for telecommunication and computer networking. Currently, FSO is capable of up to 2.5 Gbps [1] of data, voice and video communications through the air, allowing optical connectivity without requiring fiber-optic cable or securing spectrum licenses. Operate between the 780 – 1600 nm wavelengths bands and use O/E and E/O converters. FSO requires light, which can be focused by using either light emitting diodes (LEDs) or lasers (light amplification by stimulated emission of radiation). The use of lasers is a simple concept similar to optical transmissions using fiber-optic cables; the only difference is the transmission media. Light travels through air faster than it does through glass, so it is fair to classify FSO as optical communications at the speed of the light. FSO communication is considered as an alternative to radio relay link line-of sight (LOS) communication systems. This chapter is concentrate on ground-to-ground free-space laser communications. FSO components are contain three stages: transmitter to send of optical radiation through the atmosphere obeys the Beer-Lamberts`s law, free space transmission channel where exist the turbulent eddies (cloud, rain, smoke, gases, temperature variations, fog and aerosol) and receiver to process the received signal. Typical links are between 300 m and 5 km, although longer distances can be deployed such as 8–11 km are possible depending on the speed and required availability. The importance of this chapter is to introduce the FSO technique step by step.

We will briefly focus on concept of FSO technology in section 1. Section 2 presents an optical wireless transceiver design and FSO main components and transmission media. Mathematical model of atmospheric turbulence of FSO is illustrated in section 3. Second part of this study is a case study to adapt between theoretical and practical parts of FSO technique, where series of simulations results are demonstrated and analyzed. In section 4, we demonstrate the first practical part, simulation results and discussion of geometric loss and total attenuation. The second part of case study explores the optical link budget is presented in section 5. Third part of case study shows the simulation results of BER and SNR of this proposed work is demonstrated in section 6. Section 7 presents some concluding remarks. Finally, we propose some important questions related to this chapter for self-evaluation.

1.1.2. FSO applications [1,2]

- Telecommunication and computer networking
- Point-to-point LOS links
- Temporary network installation for events or other purpose as disaster recovery
- For communications between spacecraft, including elements of satellite constellation
- Security applications
- Military application: (its potential for low electromagnetic emanation when transferring sensitive data for air forces)
- Metro network extensions: carriers can deploy FSO to extend existing metropolitan area fiber rings, to connect new networks, and, in their core infrastructure, to complete SONET rings.
- Enterprise connectivity: the ease with which FSO links can be installed makes them a natural for interconnecting local area network segments that are housed in buildings separated by public streets or other right-of-way property.
- Fiber backup: FSO may also be deployed in redundant links to backup fiber in place of a second fiber link.
- Backhaul: FSO can be used to carry cellular telephone traffic from antenna towers back to facilities wired into the public switched telephone network.
- Service acceleration: FSO can be also used to provide instant service to fiber-optic customers while their fiber infrastructure is being laid.
- Last-Mile access: In today’s cities, more than 95% of the buildings do not have access to the fiber optic infrastructure due to the development of communication systems after the metropolitan areas. FSO technology seems a promising solution to the connection of end-users to the service providers or to other existing networks. Moreover, FSO provides high-speed connection up to Gbps, which is far more beyond the alternative systems.

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The advantages and disadvantages of FSO are as following [1,2]:

1.1.3. FSO Advantages

- Long distance up to 8 km.
- High bit rates speed rates: the high bandwidth capability of the fiber optic of 2.5 Gbps to 10 Gbps achieved with wavelength division multiplexing (WDM). Modern systems can handle up to 160 signals and can thus expand a basic 10 Gbit/s system over a signal fiber pair to over 1.6 Tbit/s.
- Immunity from electromagnetic interference: secure cannot be detected with RF meter or spectrum analyzer, very narrow and directional beams
- Invisible and eye safe, no health hazards so even a butterfly can fly unscathed through a beam
- Low bit error rates (BER)
- Absence of side lobes
- Deployment of FSO systems quickly and easily
- No Fresnel zone necessary
- Low maintenance (Practical)
- Lower costs as compared to fiber networks (FSO costs are as low as 1/5 of fiber network costs).
- License-free long-range operation (in contrast with radio communication)

1.1.4. FSO disadvantages

For terrestrial applications, the principal limiting factors are:

Beam dispersion, atmospheric absorption, rain, fog, snow, interference from background light sources (including the sun), shadowing, pointing stability in wind, and pollution.

1.1.5. Comparison between FSO vs. fiber optics vs. other technologies

In the future fiber optics replaced by FSO for the following reasons:

- Optics is the study of the behavior and properties of light
- Optical fibers can carry a laser beam for long distances
- Most of the recent large effort of digging up the ground and laying down new fiber has been directed towards extending the fiber optic backbone to new central offices, and not laying fiber directly to the customer
- Like fiber, FSO uses lasers to transmit data, but instead of enclosing the data stream in a glass fiber, it is transmitted through the air.

1.2. Light and electromagnetic spectrum

The electromagnetic spectrum is the range of all possible frequencies of electromagnetic radiation. The "electromagnetic spectrum" of an object has a different meaning, and is instead the characteristic distribution of electromagnetic radiation emitted or absorbed by that particular object. The electromagnetic spectrum extends from below the low frequencies used for modern radio communication to gamma radiation at the short-wavelength (high-frequency) end, thereby covering wavelengths from thousands of kilometers down to a fraction of the size of an atom. The limit for long wavelengths is the size of the universe itself, while it is thought that the short wavelength limit is in the vicinity of the Planck length, although in principle the spectrum is infinite and continuous. Most parts of the electromagnetic spectrum are used in science for spectroscopic and other probing interactions, as ways to study and characterize matter. In addition, radiation from various parts of the spectrum has found many other uses for communications and manufacturing (see electromagnetic radiation for more applications).

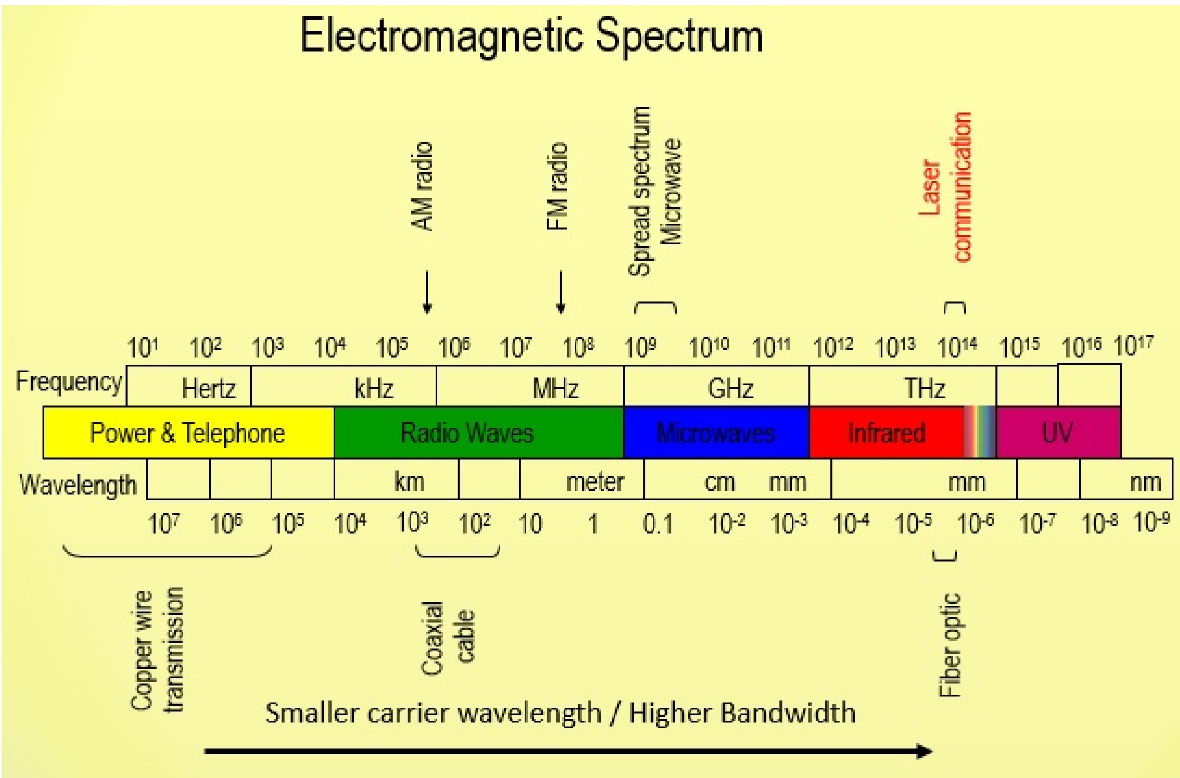

Figure 1. The electromagnetic spectrum.

The electromagnetic spectrum as demonstrated in Fig. 1, can be expressed in term of wavelength, frequency, or energy. Wavelength (λ), frequency (ν) are related by the expression [3]. The higher the frequency, the higher the energy.

$$\lambda = \frac{c}{\nu} \tag{1}$$

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Where c is the speed of light ($2.998 \times 10^8\ m/s$). The energy of the various components of the electromagnetic spectrum is given by the expression

$$E = h\nu \tag{2}$$

Where h is Planck`s constant = 6.63×10^{-34} Joule seconds. The units of wavelength are meters with the terms microns (denoted μm and equal to $10^{-6}\ m$) and nanometers ($10^{-9}\ m$) being used just as frequently. Frequency is measured in Hertz (Hz), with one Hertz being equal to one cycle of one cycle of sinusoidal wave per second. A commonly used unit of energy is the electron-volt.

There are several transmission windows that are nearly transparent (attenuation < 0.2 dB/km), between 780 nm and 1600 nm wavelength range. These windows are located around several specific center wavelengths:

- 850 nm

Characterized by low attenuation, the 850 nm window is very suitable for FSO operation. In addition, reliable, high-performance, and inexpensive transmitter and detector components are generally available and commonly used in today's service provider networks and transmission equipment. Highly sensitive silicon avalanche photo diode (APD) detector technology and advanced vertical cavity surface emitting laser (VCSEL) technology can be used for operation in this atmospheric window [4].

- 1060 nm

The 1060 nm transmission window shows extremely low attenuation values. However, transmission components to build FSO system in this wavelength range are very limited and are typically bulky (e.g. YdYAG solid state lasers). Because this window is not specially used in telecommunications systems, high-grade transmission components are rare. Semiconductor lasers especially tuned to the nearby 980 nm wavelength (980 nm pump lasers for fiber amplifiers) are commercially available. However, the 980 nm wavelength range experiences atmospheric attenuation of several dB/km even under clear weather conditions.

- 1250 nm

The 1250 nm transmission window offers low attenuation, but transmitters operating in this wavelength range are rare. Lower power telecommunications grade lasers operating typically between 1280-1310 nm are commercially available. However, atmospheric attenuation increases drastically at 1290 nm, making this wavelength only marginally suitable for free space transmission.

- 1550 nm

The 1550 nm band is well suited for free space transmission due to its low attenuation, as well as the proliferation of high-quality transmitter and detector components. Components include very high-speed semiconductor laser technology suitable for WDM operation as well as amplifiers (EDFA, SOA) used to boost transmission power. Because of the attenuation properties and component availability at this range, development of WDM free space optical systems is feasible.

1.3. Laser principles

A laser is similar in function to an LED, but somewhat different both in how it functions and in its characteristics. The idea of stimulated emission of radiation originated with Albert Einstein around 1916. Until that time, physicists had believed that a photon could interact with an atom only in two ways: The photon could be absorbed and raise the atom to a higher energy level, or the photon could be emitted by the atom when it dropped into a lower energy level [5].

Figure 2 shows the typical energy diagram (term scheme) of an atom. An electron can be moved into a higher energy level by energy provided from the outside. As a basic rule, not all transitions are allowed, and the time that an electron stays in a higher energy state before it drops to a lower energy level varies. When the electron drops from a higher to a lower level, energy is released. A radiative transition that involves the emission of a photon in the visible or infrared spectrum requires a certain amount of energy difference between both energy levels.

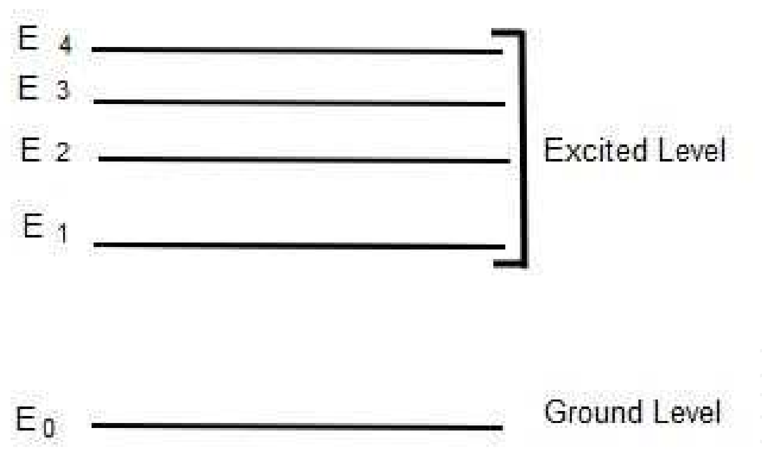

Figure 2. Energy level diagram.

$$I = \frac{c}{|E_i - E_j| / h} = \frac{1.2398}{E_i - E_h} \tag{3}$$

For ease of understanding, we will describe laser operation by using only two energy levels. Figure 3 illustrates the different methods of photon interaction [5].

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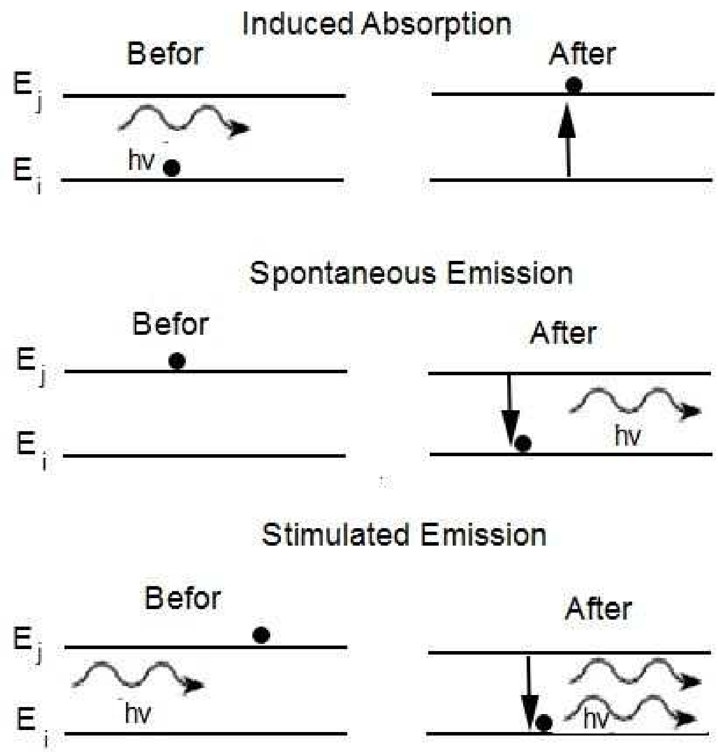

Figure 3. Understanding laser operation.

There are three possibilities:

- Induced absorption: an incoming photon whose wavelength matches the difference between the energy levels E_j and E_i can be absorbed by an atom that is in the lower energy state. After this interaction process, the photon disappears, but its energy is used to raise the atom to an upper energy level.

- Spontaneous emission: an atom in the upper energy level can spontaneously drop to the lower level. The energy that is released during this transition takes the form of an emitted photon. The wavelength of the photon corresponds to the energy difference between the energy states E_j and E_i. This resembles the process of electron-hole recombination, which resulted in the emission of a photon in the LED structure. Gas-filled fluorescent lights operate through spontaneous emission.

- Stimulated emission: an atom in the upper level can drop to the lower level, emitting a photon with a wavelength corresponding to the energy difference of the transition process. The actual emission process is induced by an incoming photon whose wavelength matches the energy transition level of the atom. The stimulated photon will be emitted in phase with the stimulating photon, which continues to propagate.

When these three processes take place in a media such as a solid-state material or gas-filled tube, many atoms are involved. If more atoms are in the ground state (or lower excited level) than in the upper one, the number of photons entering the material will decrease due to absorption.

However, if the number of photons in the upper level exceeds the number of photons in the lower level, a condition called population inversion is created. Laser operation requires the state of population inversion because under these circumstances, the number of photons increases as they propagate through the media due to the fact that more photons will encounter upper-level atoms than will meet lower-level atoms. Keep in mind that upper-level atoms cause the generation of additional photons, whereas lower-level atoms would absorb photons. A medium with population inversion has gain and has the characteristics of an amplifier.

A laser is a high-frequency generator, or oscillator. To force the system to oscillate, it needs amplification, feedback, and a tuning mechanism that establishes the oscillation frequency. In a radio-frequency system, such feedback can be provided by filtering the output signal with a frequency filter, connecting the output signal back to the input, and electronically amplifying the signal before it is coupled back into the input stage. In the case of a laser, the medium provides the amplification. Therefore, a medium capable of laser operation is often referred to as active media. For more details about fundamental of FSO technology, readers merely can refer to reference [5], chapter 2.

1.3.1. Laser diodes

The entire commercial free-space optics industry is focused on using semiconductor lasers because of their relatively small size, high power, and cost efficiency. Most of these lasers are also used in fiber optics; therefore, availability is not a problem. From the semiconductor design point of view, two different laser structures are available: edge emitting lasers and surface-emitting lasers. With an edge emitter, the light leaves the structure through a small window of the active layer and parallel to the layer structure. Surface emitters radiate through a small window perpendicular to the layer structure.

Edge emitters can produce high power. More than 100 milliwatts at modulation speeds higher than 1 GHz are commercially available in the 850 nm wavelength range. The beam profile of edge-emitting diodes is not symmetrical. A typical value for this elliptical radiation output pattern is 20 × 35 degrees. This specific feature can cause a problem when the output power has to be coupled efficiently into a fiber and external optics such as cylindrical lenses are used to increase the coupling efficiency. Surface-emitting diodes typically produce less power output. However, the beam pattern is close to being symmetrical or round. A typical value for the beam divergence angle is 12 degrees. This feature is beneficial for coupling light into a (round) optical fiber. Besides discussing basic designs of semiconductor lasers, we will also provide information regarding WDM laser sources and look into Erbium Doped Fiber Amplifiers/lasers that have been discussed recently for use in FSO systems.

1.3.2. Basic designs of optical lenses

A lens is a piece of glass or other transparent material that refracts light rays in such a way that they can form an image. Lenses can be envisioned as a series of tiny refracting prisms, and

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each of these prisms refracts light to produce its own image. When the prisms act together, they produce an image that can be focused at a single point.

Lenses can be distinguished from one another in terms of their shape and the materials from which they are made. The shape determines whether the lens is converging or diverging. The material has a refractive index that determines the refractive properties of the lens. The horizontal axis of a lens is known as the principal axis. A converging (convex) lens directs incoming light inward toward the center axis of the beam path. Converging lenses are thicker across their middle and thinner at their upper and lower edges. When collimated[1] (parallel) light rays enter a converging lens, the light is focused to a point. The point where the light converges is called the focal point and the distance between the lens and the focal point is called focal length. A diverging (convex) lens directs incoming rays of light outward away from the axis of the beam path. Diverging lenses are thinner across their middle and thicker at their upper and lower edges. Figure 4 illustrates the behavior of converging and diverging lenses [6].

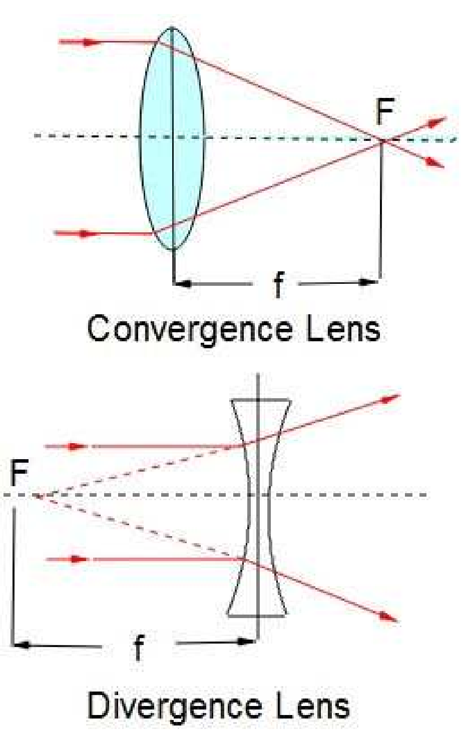

Figure 4. Converging and diverging lenses.

The focal length (*f*) of an optical system is a measure of how strongly the system converges or diverges light. For an optical system in air, it is the distance over which initially collimated rays are brought to a focus. A system with a shorter focal length has greater optical power than one with a long focal length; that is, it bends the rays more strongly, bringing them to a focus in a shorter distance. The focal length *f* is then given by

1 Make (rays of light or particles) accurately parallel: (as adjective collimated) a collimated electron beam.

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v} \tag{4}$$

where u is the distance between the light source and the lens, and v is the distance between the lens and the screen.

1.4. Important definitions

After illustrating the basic concepts of FSO, we return to the important definitions related to the laser power reduction due to atmospheric channel effects phenomena. These definitions are considered as the core principle of FSO transmission channel turbulence namely atmosphere, aerosol, absorption, scattering, and radiance etc. Absorption and scattering are related to the loss and redirection of the transmitted energy. The majority of these definitions will be discussed in detail in the case study of this chapter (section 4).

An atmosphere is a layer of gases surrounding a planet or other material body material of sufficient mass that is held in place by the gravity of the body. An atmosphere is more likely to be retained if the gravity is high and the atmosphere's temperature is low. Earth atmospheric, which is mostly nitrogen, also contains oxygen used by most organism for respiration and carbon dioxide used by plants, algae and cyanobacteria for photosynthesis, also protects living organisms from genetic damage by solar ultraviolet radiation. Another definition of an atmosphere is the envelope of gases surrounding the earth or another planet.

An aerosol is defined as a colloidal system of solid or liquid particles in a gas. An aerosol includes both the particles and the suspending gas, which is usually air. This term describes an aero-solution, clouds of microscopic particles in air. According to the literature, the size range of aerosol particles to be only from 0.1 to 1 μm another authors indicate that the size of aerosol is between 0.01 and 10 μm in radius. Another definition of aerosol is extremely-fine liquid droplets or solid particles that remain suspended in air as **fog** or **smoke**.

Fog is a thick cloud of tiny water droplets suspended in the atmosphere at or near the earth's surface that obscures or restricts visibility (to a greater extent than mist; strictly, reducing visibility to below 1 km).

Smoke is a visible suspension of carbon or other particles in air, typically one emitted from a burning substance.

Haze is traditionally an atmospheric phenomenon where dust, smoke and other dry particles obscure the clarity of the sky.

Dust is a fine powder made up of very small pieces of earth or sand.

Absorption of the light is the decrease in intensity of optical radiation (light) as it passes through a material medium owing to its interaction with the medium. In the process of absorption, the energy of the light is converted to different forms of internal energy of the medium; it may be completely or partially re-emitted by the medium at frequencies other than the frequency of the absorbed radiation.

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Light scattering is a form of scattering in which light is the form of propagating energy which is scattered. Light scattering can be thought of as the deflection of a ray from a straight path, for example by irregularities in the propagation medium, particles, or in the interface between two media. Deviations from the law of reflection due to irregularities on a surface are also usually considered to be a form of scattering. When these are considered to be random and dense enough that their individual effects average out, this kind of scattered reflection is commonly referred to as diffuse reflection. Scattering has different types as Rayleigh, Mie, Tyndall, Brillion, and Raman Scattering.

Radiance erasures of the quantity of radiation that passes through or is emitted from a surface and falls within a given solid angle in a specified direction. Radiance is also used to quantify emission of neutering and other particles.

Radiance (in Watts): total amount of energy that flows the light source.

Attenuation is the gradual loss in intensity of any kind of flux through a medium. Attenuation affects the propagation of waves and signals transmission media.

Scintillation is a flash of light produced in a transparent material by the passage of a particle (an electron, an alpha particle an ion, or a high-energy photon).

The process of scintillation is one of luminescence whereby light of a characteristic spectrum is emitted following the absorption of radiation. The emitted radiation is usually less energetic than that absorbed. Scintillation is an inherent molecular property in conjugated and aromatic organic molecules and arises from their electronic structures. Scintillation also occurs in many inorganic materials, including salts, gases, and liquids.

1.5. Lasers and eye safety

According to reference [5], certain high-power laser beams used for medical procedures can damage human skin, but the part of the human body most susceptible to lasers is the eye. Like sunlight, laser light travels in parallel rays. The human eye focuses such light to a point on the retina, the layer of cells that responds to light. Like staring directly into the sun, exposure to a laser beam of sufficient power can cause permanent eye injury.

For that reason, potential eye hazards have attracted considerable attention from standards writers and regulators. The standards rely on parameters such as laser wavelength, average power over long intervals, peak power in a pulse, beam intensity, and proximity to the laser. Laser wavelength is important because only certain wavelengths—between about 400 nm and 1,550 nm—can penetrate the eye with enough intensity to damage the retina. The amount of power the eye can safely tolerate varies with wavelength. This is dominated by the absorption of light by water (the primary component in the eye) at different wavelengths.

The vitreous fluid of the eye is transparent to wavelengths of 400—1,400 nm. Thus, the focusing capability of the eye causes approximately a 100,000-to-1 concentration of the power to be focused on a small spot of the retina. However, in the far infrared (1,400 nm and higher), such light is not transmitted by the vitreous fluid, so the power is less likely to be transferred to the retina. Although damage to the corneal surface is a possibility, the focusing capabilities of the eye do not lead to large magnification of power densities. Therefore, much greater power is required to cause damage. The relevance of this is that lasers deployed in FSO that utilize wavelengths greater than 1,400 nm are allowed to be approximately 100 times as powerful as FSO equipment operating at 850 nm and still be considered eye safe. This would be the "killer app" of FSO except that the photo diode receiver technologies suffer reduced sensitivity at greater than 1,400 nm, giving back a substantial portion of the gain. Also, lasers that operate at such wavelengths are more costly and less available. Nevertheless, at least one FSO manufacturer has overcome these obstacles and currently offers equipment deploying multiple 1,550 nm lasers.

With respect to infrared radiation, the absorption coefficient at the front part of the eye is much higher for longer wavelength (> 1,400 nm) than for shorter wavelength. As such, damage from the ultraviolet radiation of sunlight is more likely than from long wavelength infrared. Eye response also differs within the range that penetrates the eyeball (400 nm—1,400 nm) because the eye has a natural aversion response that makes it turn away from a bright visible light, a response that is not triggered by an (invisible) infrared wavelength longer than 0.7 μm. Infrared light can also damage the surface of the eye, although the damage threshold is higher than that for ultraviolet light.

High-power laser pulses pose dangers different from those of lower-power continuous beams. A single high-power pulse lasting less than a microsecond can cause permanent damage if it enters the eye. A low-power beam presents danger only for longer-term exposure. Distance reduces laser power density, thus decreasing the potential for eye hazards.

2. Optical wireless transceiver design

FSO contains three components: transmitter, free space transmitted channel line of sight, and receiver. Transmitter is considered as an optical source 1-laser diode (LD) or 2-light emitting diode (2-LED) to transmit of optical radiation through the atmosphere follows the Beer-Lamberts's law as indicated in subsection 3.6 Eq. 34.

FSO link is demonstrated as in Fig. 5. The selection of a laser source for FSO applications depends on various factors. It is important that the transmission wavelength is correlated with one of the atmospheric windows. As noted earlier, good atmospheric windows are around 850 nm and 1550 nm in the shorter IR wavelength range. In the longer IR spectral range, some wavelength windows are present between 3–5 micrometers (especially 3.5–3.6 micrometers) and 8–14 micrometers [5]. However, the availability of suitable light sources in these longer wavelength ranges is pretty limited at the present moment. In addition, most sources need low temperature cooling, which limits their use in commercial telecommunication applications. Other factors that impact the use of a specific light source include the following:

- Price and availability of commercial components
- Transmission power
- Lifetime

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- Modulation capabilities
- Eye safety
- Physical dimensions
- Compatibility with other transmission media such as fiber.

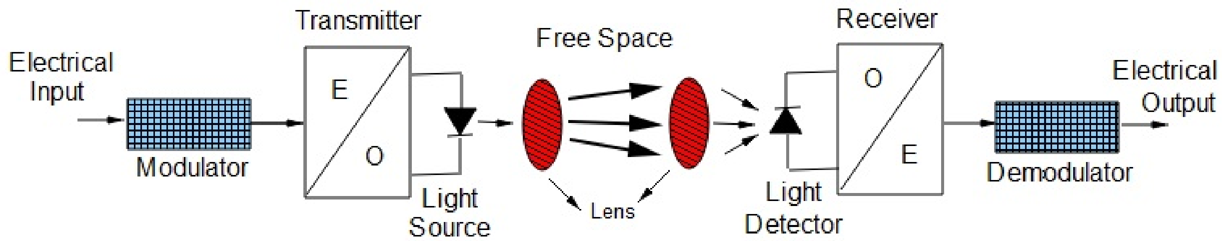

Figure 5. Block diagram of an optical wireless link showing the front end of an optical transmitter and receiver [7].

Electrical input is a network traffic into pulses of invisible light representing 1`s and 0`s. The transmitter, which consists of two part main parts: an interface circuit and source driver circuit, converts the input signal to an optical signal suitable for transmission. The drive circuit of the transmitter transforms the electrical signal to an optical signal by varying the current follow through the light source. Transmitter function is to project the carefully aimed light pulses into the air. This optical light source can be of two types:

1. A light-emitting diode (LED) or
2. A laser diode (LD).

The information signal modulates the field generated by the optical source. The modulated optical field then propagates through a free-space path before arriving at the receiver. In the receiver side, transmitted data realizes inverse operations i.e., photo detector converts the optical signal back into an electrical form as indicated in previous figure. In other words, a receiver at the other end of the link collects the light using lenses and/or mirrors. Received signal converted back into fiber or cooper and connected to the network. Reverse direction data transported the same way (full duplex). We can see, anything that can be done in fiber can be done with FSO.

Equation (5) illustrates the data rate of FSO system:

$$Data\ Rate\left[{}^{bits}\!/_{sec}\right] = \frac{1}{\eta} P_r\left[\frac{photons}{sec}\right] \qquad (5)$$

Where P_r is a received power, and η is a received power sensitivity of the receiver [photons/bit].

Small angles – divergence angle and spot size between transmitter and receiver are presented in Fig. 6.

$$1^{\circ} \approx 17\ mrad \rightarrow 1\ mrad \approx 0.0573^{\circ}$$

θ is a divergence angle between transmitter and receiver FSO units.

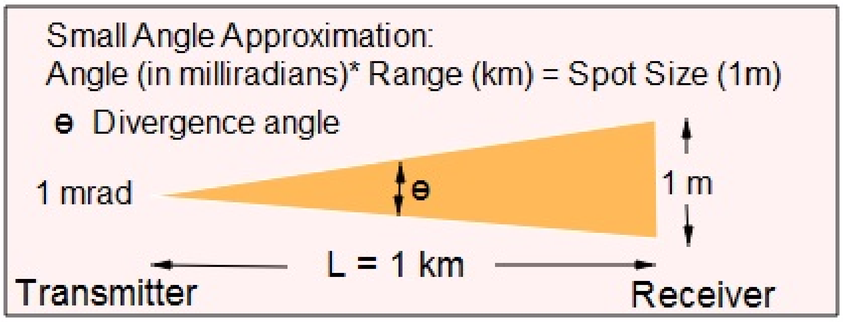

Figure 6. Small angles – divergence and spot size between transmitter and receiver.

The geometric path loss for an FSO link depends on the beam-width of the optical transmitter, the path length (L), and the divergence angle (θ). Transmitter and receiver aperture diameters are quantifiable parameters, and are usually specified by manufacturer. Table (1) illustrates the relation of divergence in (mrad), range in (km), and spot diameter in (inches or feet).

Divergence	Range	Spot Diameter
0.5 mrad	1.0 km	~ 0.5 m (~ 20 in)
2.0 mrad	1.0 km	~ 2.0 m (~ 6.5 ft)
4.0 mrad (~ ¼ deg)	1.0 km	~ 4.0 m (~ 13.0 ft)

Table 1. The divergence, range, and spot diameter.

3. Mathematical model of atmospheric turbulence

The atmospheric attenuation is one of the challenges of the FSO channel, which may lead to signal loss and link failure. The atmosphere not only attenuates the light wave but also distorts and bends it. Transmitted power of the emitted signal is highly affected by scattering and turbulence phenomena. 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.

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3.1. Aerosol

Aerosols are particles suspended in the atmosphere with different concentrations. They have diverse nature, shape, and size. Aerosols can vary in distribution, constituents, and concentration. As a result, the interaction between aerosols and light can have a large dynamic, in terms of wavelength range of interest and magnitude of the atmospheric scattering itself. Because most of the aerosols are created at the earth's surface (e.g., desert dust particles, human-made industrial particulates, maritime droplets, etc.), the larger concentration of aerosols is in the boundary layer (a layer up to 2 km above the earth's surface). Above the boundary layer, aerosol concentration rapidly decreases. At higher elevations, due to atmospheric activities and the mixing action of winds, aerosol concentration becomes spatially uniform and more independent of the geographical location. 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 [8].

Type	Radius (μm)	Concentration (in 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 5×10^{3}	N/A
Hail	5×10^{3} to 5×10^{4}	N/A

Table 2. 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 (2) [7,9].

3.2. Visibility Runway Visual Range (RVR)

Visibility was defined originally for meteorological needs, as a quantity estimated by a human observer. It defined as (Kruse model) means of the length where an optical signal of 550 nm is reduced to 0.02 of its original value [10]. However, this estimation is influenced by many subjective and physical factors. The essential meteorological quantity, namely the transparency of the atmosphere, can be measured objectively and it is called the Runway Visual Range (RVR) or the meteorological optical range [11]. Some values of atmospheric attenuation due to scattering based on visibility are presented in Table (3).

Visibility S (Line of Sight) (km)	λ = 800 nm (dB/km)	λ = 2500 nm (dB/km)
0.5	32.5	30.8
0.7	23	21
0.9	18	16
1.1	14.5	12.5
1.3	12	10
1.5	10	8.33
Source:		

Table 3. Variation in atmospheric attenuation due scattering based on visibility (data obtained from [7,12]).

When the length difference between the two optical paths varies, the energy passes through minima and maxima. The visibility V is defined by:

$$V = \frac{I_{Max} - I_{min}}{I_{Max} + I_{min}} \tag{6}$$

The visibility depends on the degree of coherence of the source, on the length difference between the paths as well as on the location of the detector with respect to the source. The coherence between the various beams arriving at the detector also depends on the crossed media: for example the diffusing medium can reduce the coherence. For links referred to as "in direct sight" links, coherent sources can be used, provided that parasitic reflections do not interfere with the principal beam, inducing modulations of the detected signal [11].

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 [13].

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 varying with time and depend on the current local conditions and weather. In general, the atmospheric attenuation is given by the following Beer's law equation [14]:

$$\tau = \exp(-\beta L), \tag{7}$$

where,

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τ is the atmospheric attenuation;

β is the total attenuation coefficient and given as

$$\beta = \beta_{abs}\beta_{scat}; \tag{8}$$

L is the distance between transmitter and receiver (unit: km);

β_{abs} is the molecular and aerosol absorption, this parameter value is considered as too small so, we can neglected;

β_{scat} is the molecular and aerosol scattering.

3.3.1. 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 [15].

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 [11], shown in Fig. 7, 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 [7].

It is possible to calculate absorption coefficients from the concentration of the particle and the effective cross section such as [16,17]:

$$\beta_{abs} = \alpha_{abs} N_{abs}\left[\frac{1}{km}\right] \tag{9}$$

Where:

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

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

An 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. Another reason for ignoring absorption effect is to select wavelengths that fall inside the transmittance windows in the absorption spectrum [18].

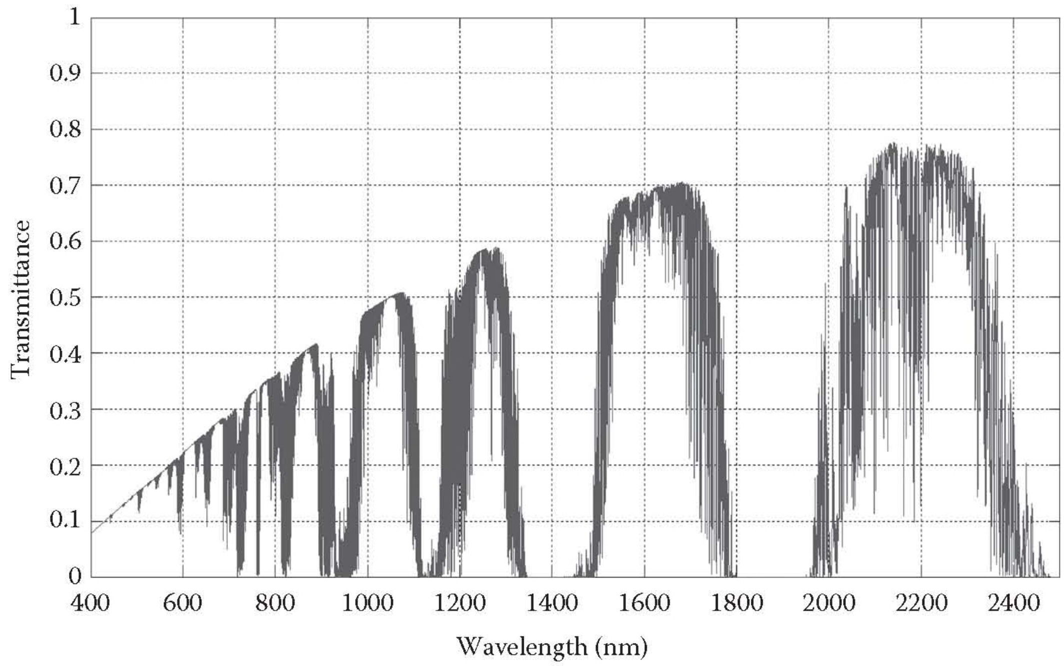

Figure 7. Atmospheric transmittance window with absorption contribution.

3.3.2. 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 [10].

There are three main types of scattering: (1) Rayleigh scattering, (2) Mie scattering, and (3) non-selective scattering. Figure 8 illustrates the patterns of Rayleigh, Mie and non-Selective scattering.

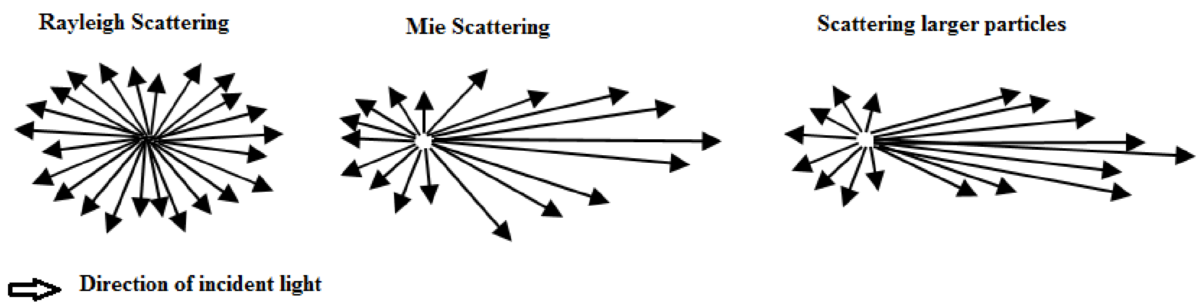

Figure 8. Patterns of Rayleigh, Mie and Non-selective scattering.

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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 [19]. If $x_0 << 1$, the backward lobe becomes larger and the side lobes disappear as shown in Fig. 8 [20] and the scattering process is termed as Rayleigh scattering. If $x_0 \approx 1$, the backward lobe is symmetrical with the forward lobe as shown in Fig. 8 and then it is Mie scattering. For $x_0 >> 1$, the particle presents a large forward lobe and small side lobes that start to appear as shown in Fig. 8 [20] and the scattering process is termed as non-selective scattering. The scattering process for different scattering particles present in the atmosphere is summarized in Table (4) [21]. It is possible to calculate the scattering coefficients from the concentration of the particles and the effective cross section such as [16]:

$$\beta_{scat} = \alpha_{scat} N_{scat} [1 / km] \tag{10}$$

Where:

β_{scat}: is either Rayleigh (molecular) β_m or Mie (aerosols) β_a scattering.

α_{scat}: is a cross-section parameters $[km^2]$.

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

The total scattering can be written as:

$$\beta_{scat} = \beta_m + \beta_a [1 / km] \tag{11}$$

Type of particles	Radius (μm)	Size parameter (X_o)	Scattering regime
Air molecules	0.0001	0.00074	Rayleigh
Haze particles	0.01 - 1	0.074 – 7.4	Rayleigh - Mie
Fog droplets	1 - 20	7.4 – 147.8	Mie - Geometrical
Rain droplets	100 - 1000	740 - 7400	Geometrical
Snow flakes	1000 - 5000	7400 - 37000	Geometrical

Table 4. Typical atmospheric scattering parameters, with size parameter.

3.3.2.1. 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 [16]:

$$\beta_m = \alpha_m N_m [1 / km] \tag{12}$$

Where:

α_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 (λ^{-4}) as the following relationship:

$$\alpha_m = \frac{8\pi^3(n^2 - 1)^2}{3N^2\lambda^4}[km^2] \tag{13}$$

Where:

n: is the index of refraction.

λ: 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 [10].

3.3.2.2. MIE (Aerosol) scattering

Mie scattering occurs when the particle diameter is equal or larger than one-tenth the incident laser beam wavelength, see Table 4. 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 μm – 2 μm). This makes fog and haze a keys contributor to optical power/irradiance attenuation. The attenuation levels are too high and obviously are not desirable [22].

The attenuation due to Mie scattering can reach values of hundreds of dB/km [19,23] (with the highest contribution arising from fog). The Mie scattering coefficient expressed as follows [10]:

$$\beta_a = \alpha_a N_a [1 / km] \tag{14}$$

Where:

α_a: is the Mie scattering cross-section [km^2].

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

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 [24]. Due to the fact that the visibility is an easily obtainable parameter, either from airport or weather data, the scattering coefficient β_a can be expressed according to visibility and wavelength by the following expression [11]:

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$$\beta_a = \left(\frac{3.91}{V}\right)\left(\frac{0.55\mu}{\lambda}\right)^i \tag{15}$$

Where:

V: is the visibility (Visual Range) $[km]$.

λ: is the incident laser beam wavelength $[\mu m]$.

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:

$$i = 1.6 \;\; for\; V > 50\; km.$$
$$i = 1.3 \;\; for\; 6\; km \leq V \leq 50\; km.$$
$$i = 0.585\; V^{1/3} \;\; for\; V < 6\; km.$$

Since we are neglecting the absorption attenuation at wavelength of interest and Rayleigh scattering at terrestrial altitude and according to Eq. 8 and Eq. 11 then:

$$\beta_{scat} = \beta_a \tag{16}$$

The atmospheric attenuation τ is given as:

$$\tau = \exp\left(-\beta_a L\right) \tag{17}$$

The atmospheric attenuation in dB, τ can be calculated as follows:

$$\tau = 4.3429 \beta_a L \;\; [dB] \tag{18}$$

3.3.2.3. 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 [11].

Rainfall effects on FSO systems:

Scattering due to rainfall is called non-selective scattering, this is because the radius of raindrops (100 – 1000 μm) 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 [24]. 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 [14]. The rain scattering coefficient can be calculated using Stroke Law [25]:

$$\beta_{rain\ scat} = \pi a^2 N_a Q_{scat}\left(\frac{a}{\lambda}\right) \tag{19}$$

Where:

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

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

Q_{scat}: is the scattering efficiency.

The raindrop distribution N_a can be calculated using equation following:

$$N_a = \frac{R}{1.33(\pi a^3) V_a} \tag{20}$$

Where:

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

V_a: is the limit speed precipitation.

Limiting speed of raindrop [25] is also given as:

$$V_a = \frac{2a^2 \rho g}{9\eta} \tag{21}$$

Where:

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

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

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

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

$$\tau = \exp\left(-\beta_{rain\ scat} L\right) \tag{22}$$

For more details about several weather conditions and the corresponding visibility at various wavelengths readers can refer to references [26,27].

3.4. 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 [28,29]. 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. 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 [30]. The refractive index can be described by the following relationship [31]:

$$n - 1 \approx 79 \times \frac{P}{T} \tag{23}$$

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. 9. If the sizes of the turbulence eddies are smaller than the beam diameter and so the laser beam bends, they become distorted as in Fig. 10. 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 see Fig. 10.

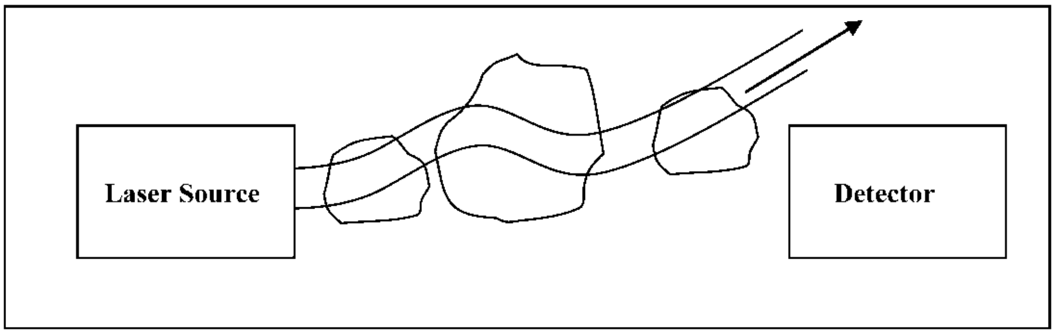

Figure 9. Laser beam Wander Due to turbulence cells that are larger than the beam diameter.

3.4.1. 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

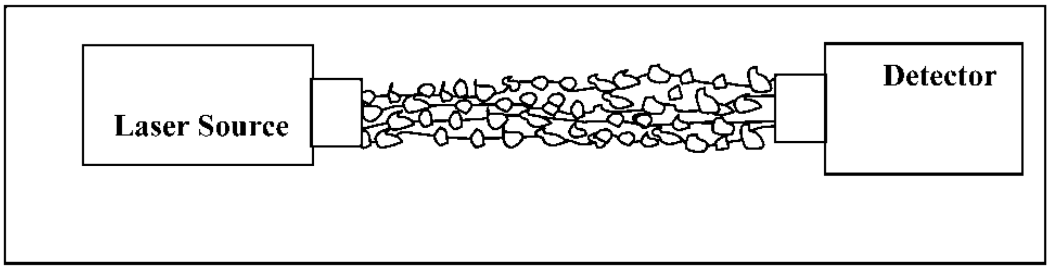

Figure 10. Scintillation or fluctuations in beam intensity at the receiver due to turbulence cells that is smaller than the beam diameter.

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 [8].

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 $10^{-17}m^{-2/3}$, while for a strong turbulence it can be up to $10^{-13}m^{-2/3}$ 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 [32] given by:

$$C_n^2(h) = 0.00594(\upsilon / 27)^2(10^{-5}h)^{10} exp\left(-\frac{h}{1000}\right) + 2.7 \times 10^{-16} exp\left(-\frac{h}{1500}\right) + A_o exp\left(-\frac{h}{100}\right) \tag{24}$$

Where:

h: is the altitude in $[\mathrm{m}]$.

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

A_0: is the turbulence strength at the ground level, $A_o = 1.7 \times 10^{-14} m^{-2/3}$.

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

3.4.2. Scintillation

Scintillation may be the most noticeable one for FSO systems. Light traveling through scintillation will experience intensity fluctuations, even over relatively short propagation paths. The scintillation index, σ_i^2 describes such intensity fluctuation as the normalized variance of the intensity fluctuations given by [8,14]:

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$$\sigma_i^2 = \frac{\langle (I - \langle I \rangle)^2 \rangle}{\langle I \rangle^2} = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1 \tag{25}$$

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 σ_i given by the following:

$$\sigma_i^2 = 1.23 C_n^2 k^{7/6} L^{\ 11/6} \tag{26}$$

Where C_n^2 is the refractive index structure, $k = 2\pi / \lambda$ is the wave number (an expression suggests that longer wavelengths experience a smaller variance), and *l* is the link range (m).

Where the Eq. 26 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 [8].

3.4.3. 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 [33]:

$$I(l,\ r) = \frac{2P_o}{\pi \omega_{eff}^2(l)} exp\left(\frac{-2r^2}{\omega_{eff}^2(l)}\right) \tag{27}$$

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:

$$\omega_{eff}(l)^2 = \omega(l)^2(1 + T) \tag{28}$$

Where:

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

$$\omega(l)^2 = \left[\omega_o^2 + \left(\frac{2L}{k\omega_o}\right)^2\right](m^2) \tag{29}$$

In which ω_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:

$$T = 1.33\sigma_i^2 \Lambda^{5/6} \tag{30}$$

While the parameter Λ is given by:

$$\Lambda = \frac{2L}{k\omega^2(l)} \tag{31}$$

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. Evidently, due to the fact that $\omega_{eff}(l) > \omega(l)$ beam will experience a loss that at beam center will be equal:

$$L_{BE} = 20\ log_{10}(\omega(l) / \omega_{eff}(l)) \tag{32}$$

3.5. Geometric Losses (GL)

The geometric path loss for an FSO link depends on the beam-width of the optical transmitter θ, its path length L and the area of the receiver aperture A_r. The transmitter power, P_t is spread over an area of $\pi(L\theta)^2 / 4$. The geometric path loss for an FSO link depends on the beam-width of the optical transmitter θ, its path length L and the area of the receiver aperture A_r. The transmitter power, P_r is spread over an area of $\pi(L\theta)^{2/4}$. Geometric loss is the ratio of the surface area of the receiver aperture to the surface area of the transmitter beam at the receiver. Since the transmit beams spread constantly with increasing range at a rate determined by the divergence, geometric loss depends primarily on the divergence as well as the range and can be determined by the formula stated as [2]:

$$\text{geometric loss} = \frac{d_2^2}{\left[d_1 + (L\theta)\right]^2} \tag{33}$$

Where:

d_2 is the diameter receiver aperture (unit: m);

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d_1 is the diameter transmitter aperture (unit: m);

θ is the beam divergence (unit: mrad);

L is the link range (unit: m).

Geometric path loss is present for all FSO links and must always be taken into consideration in the planning of any link. This loss is a fixed value for a specific FSO deployment scenario; it does not vary with time, unlike the loss due to rain attenuation, fog, haze or scintillation.

3.6. 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 [34]:

$$\frac{P_r}{P_t} = \frac{d_2^2}{\left[d_1 + (L\theta) \right]} \times \exp(-\beta L\ ), \tag{34}$$

where,

P_t is the transmitted power (unit: mW);

P_r is the received power (unit: mW);

θ is the beam divergence (unit: mrad);

β is the total scattering coefficient (unit: km^{-1}).

According to Eq. (34), the variables which 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 control is link range, which must be of a short distance to ensure that the atmospheric attenuation is not dominant in the total attenuation [35].

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

$$\sigma_1^2 = 1.23\, C_n^2 k^{7/6} L^{\ 11/6} \tag{35}$$

Here, k=$2\pi/\lambda$ is the wave number and this expression suggests that longer wavelengths experience a smaller variance, and C_n^2 is a refractive index structure parameter. Equation (35) 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.

In this chapter, we do not take into account the atmospheric turbulence, because its influence in Yemeni climate could be negligible. That means the effect of the turbulence is too small contrary to visibility and geometric loss. Therefore, we have taken into account only the total attenuation depending on visibility, and geometric loss.

An FSO communication system is influenced by atmospheric attenuation, which limits their performance and reliability. The atmospheric attenuated by fog, haze, rainfall, and scintillation has a harmful effect on FSO system. The majority of the scattering occurred on the laser beam is Mie scattering. This scattering is due to the fog and haze aerosols existed at the atmosphere and can be 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. The rain scattering (non-selective scattering) is independent on wavelength, and it does not introduce significant attenuation in wireless infrared links, it affects 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 of air. If the light is traveled by 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. To reduce total attenuation, the effect of geometric loss and atmospheric attenuation is small, as FSO system must be designed. The following section explores the simulation results of geometric loss and total attenuations for Yemeni climate.

3.7. Optical link budget

To calculate the FSO link budget several parameters taken into account as geometric loss, link margin, received power and bit error rate. The received power should be grater less the transmitted power from the source and equal the transmitted power minus total loss. In the basic free-space channel the optical field generated at the transmitter propagates only with

an associated beam spreading loss. For this system the performance can be determined directly from the power flow. The signal power received P_{Rx} [W] depends on the transmit power P_{Tx} [W], transmit and receive antenna gains G_{Tx}, G_{Rx}, and the total loss [36]

$$P_{r} = P_t + G_{Tx} + G_{Rx} - \text{total loss} \tag{36}$$

Table (5) shows the values of transmitted output power for diffuse and tracked topology (Data obtained from [7]).

In the indicated reference, they presented an expression to calculate the link distance L achievable from direct line propagation:

Data Bit Rate (Mbps)	Optical Power (Diffuse System)	Optical Power (Tracked System)	Optical Power (Cellular System)
0.1	$3 \times 10^{-2}\,W$	$6 \times 10^{-7}\,W$	$3 \times 10^{-3}\,W$
0.5	$6 \times 10^{-2}\,W$	$8 \times 10^{-7}\,W$	$5.8 \times 10^{-3}\,W$
1	$8 \times 10^{-2}\,W$	$1 \times 10^{-6}\,W$	$8 \times 10^{-3}\,W$
5	$1 \times 10^{-1}\,W$	$3 \times 10^{-6}\,W$	$1 \times 10^{-2}\,W$
10	$2.5 \times 10^{-1}\,W$	$6 \times 10^{-6}\,W$	$2 \times 10^{-2}\,W$
50	$6 \times 10^{-1}\,W$	$9 \times 10^{-6}\,W$	$3 \times 10^{-2}\,W$

Table 5. Values of transmitted output power for diffuse and tracked topology from [7].

$$L = \frac{P_t A_r T_1 T_2}{2\pi P_{rm}(1 - \cos \emptyset)} \tag{37}$$

Here, P_t represent the optical output power from the transmitter (in mW), A_r is the active area of the photodetector, T_1 is the transmittivity of the transmitter filter, T_2 is the transmittivity of the filter at the receiver, P_{rm} is the optical power required (in mW) to obtain a specific carrier-to-noise ratio at the receiver, and $\emptyset$ is the half angle of the energy related by optical source. From this expression, they calculate achievable distances (depending on the FOV), which in their case covered a range of between 10 and 20 m.

3.8. BER and SNR

Both SNR and BER are used to assess the quality of communication systems. BER performance depends on the average received power, the scintillation strength, and the receiver noise. With an appropriate design of aperture averaging, the received optical power could be increased and the effect of the scintillation can be dumped. With turbulence, the SNR is expressed as follows [37]:

$$SNR = \left(0.31 C_n^2 k^{\frac{7}{6}} l^{\frac{11}{6}}\right)^{-1} \tag{38}$$

For FSO links with an on off keying modulation scheme in BER can be written as

$$BER = \frac{exp(-SNR / 2)}{(2\pi SNR)^{0.5}} \tag{39}$$

In our model, we have assumed that the surface area of the photo detector is large enough so that the effective SNR includes the beam spreading effect, thus the effective SNR is defined as

$$SNR_{eff} = \frac{SNR}{1 + 1.33\sigma_i^2\left[\frac{2l}{k\omega(l)^2}\right]^{5/6}} \tag{40}$$

The performance and reliability of FSO communication systems are affected and limited by atmospheric attenuation. It has a harmful effect by haze, rainfall, fog, and scintillation has a harmful effect of 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 traveling 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. Practical part: Case study

In this chapter, we will take Yemeni climate as a case study to study and analyze the practical part of FSO system by series of simulations obtained results.

4.1. Simulation results and discussion of geometric loss and total attenuation

4.1.1. Geometric loss

This part illustrates the effects of geometric loss on the performance of FSO system. We calculated the value of geometric loss using Eq. (33) assuming that the link range is 1 km and beam divergence is 1 mrad at two different designs, which are considered as particular design specifications shown in Table 6, due to particular implementation especially based on the existing product available in the industry [38,39].

design	diameter of transmitter aperture	diameter of receiver aperture
design 1	8 cm	10 cm
design 2	3.5 cm	7 cm

Table 6. Diameters of transmitter and receiver aperture of an FSO system.

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There are a number of parameters that control geometric loss: transmission range, the diameter of transmitter and receiver apertures and laser beam divergence. These parameters also contribute to the design of FSO system, so that it is suitable during bad weather conditions.

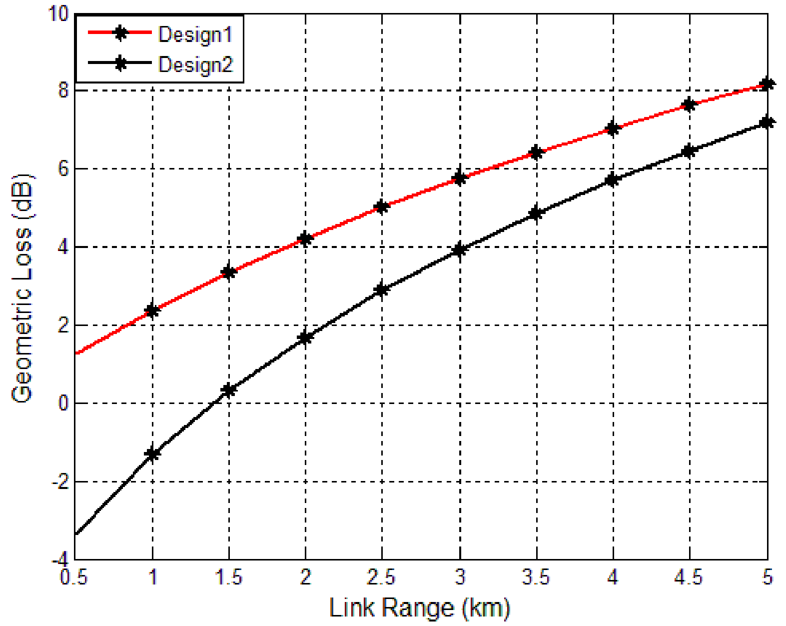

Figure 11. Geometric loss (dB) versus link range (km).

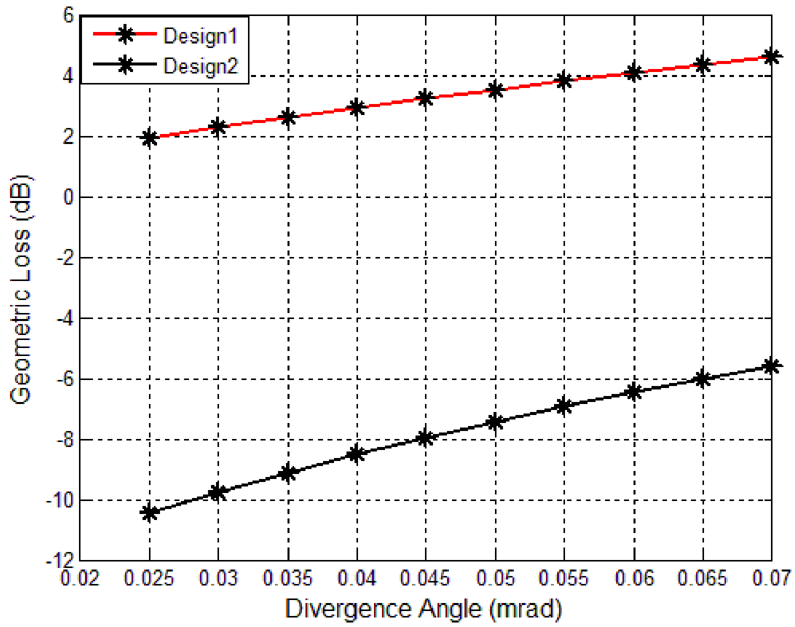

Figure 12. Geometric loss (dB) versus divergence angle (mrad).

Figure 11 shows the geometric loss versus link range using the values presented in Table 6 and divergence angle is about 0.025 mrad. The link range is in the range of 0.5 to 5.0 km. Geometric loss is proportional to link range, which shows that the link range increases with the increases of geometric loss. As demonstrated in Fig. 11 the geometric loss is 1.3 dB at 0.5 km for design 1 and -3.4 dB for design 2. While at the distance of 5km the geometric loss for design 1 reaches 8.2 dB and 7.2 dB for design 2. Figure 12 illustrates the geometric loss versus the divergence angle. The divergence angle is in the range of 0.025 to 0.07 mrad. Geometric loss is proportional to divergence angle, which suggest that when the divergence angle increases, geometric loss enhances. For a 0.025 mrad divergence angle, the geometric loss is about 1.93 dB for design 1 and -10.5 dB for design 2. For a 0.07 mrad divergence angle, the geometric loss is about 4.6 dB for design 1 and -5.6 dB for design 2. That means by using a small divergence angle of laser beam in FSO systems, geometric loss effect is minimized.

Figure 13 demonstrates the geometric loss versus the transmitter aperture diameter using the values presented in Table 1, divergence angle is about 0.025 mrad and the link range is 1 km. The transmitter aperture diameter is in the range of 2 to 22 cm. This figure shows that the transmitter aperture diameter rises with increases of the geometric loss. For transmitter aperture diameter of 2 cm, the geometric loss is about -7 dB for design 1 and -3.87 dB for design 2. For the transmitter aperture diameter of 20 cm, the geometric loss is about 7.7 dB for design 1 and 10.2 dB for design 2. That means the small transmitter aperture diameter is suggested to minimize in the geometric loss effect on FSO systems.

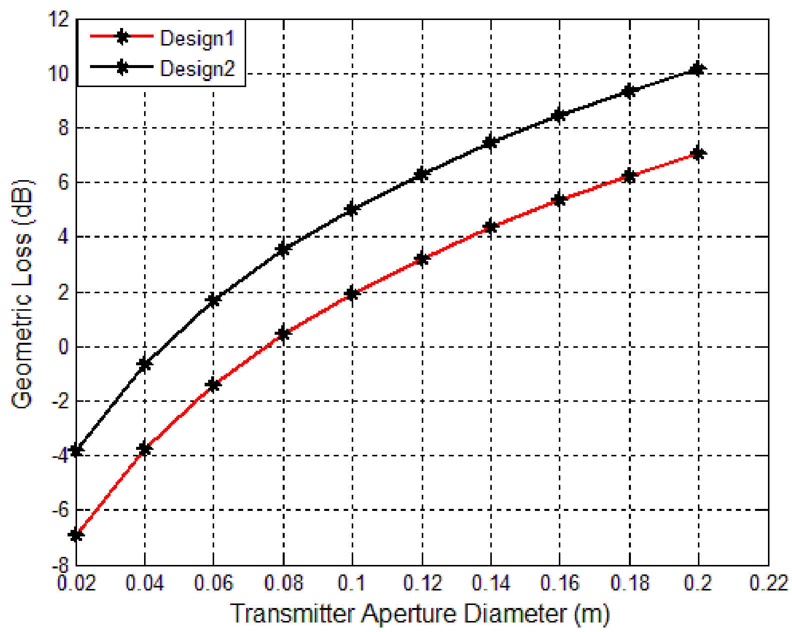

Figure 13. Geometric loss (dB) versus transmitter aperture diameter (m).

Figure 14 indicates the geometric loss versus the receiver aperture diameter using the values presented in Table 7, divergence angle is about 0.025 mrad and the link range is 1 km. When the receiver aperture diameter increases, the geometric loss decreases. For receiver aperture diameter of 2 cm, the geometric loss is about 14.4 dB for design 1 and 9.5 dB for design 2. For the receiver aperture diameter of 20 cm, the geometric loss is about -5.6 dB for design 1 and -10.5 dB for design 2.

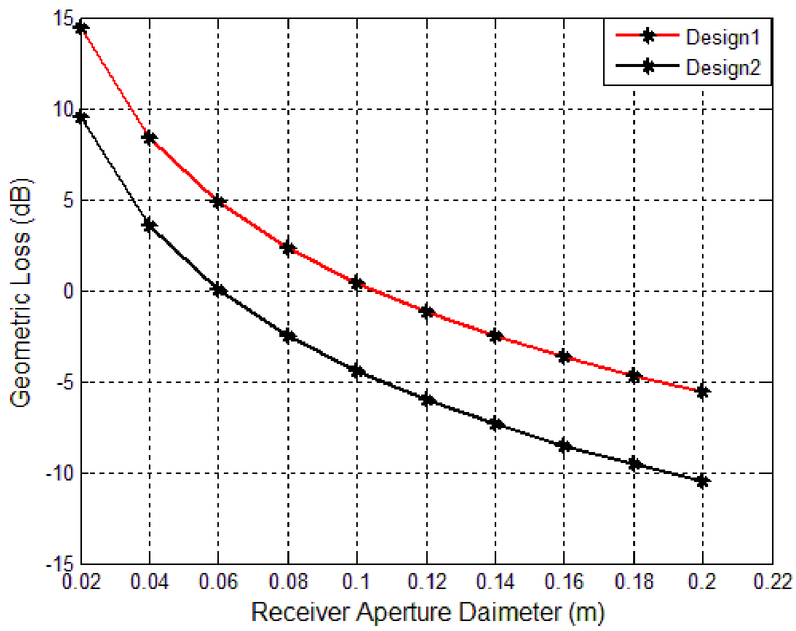

Figure 14. Geometric loss (dB) versus receiver aperture diameter (m).

That is to say that the large receiver aperture diameter will be used to reduce the geometric loss effect on the FSO systems. The results of geometric losses with design parameters are presented in Table 7. We note that the geometric loss at low values for receiver aperture diameter is high compared to the upper values. Because the aperture diameter of receiver is smaller than aperture diameter of transmitter. At a result, the aperture diameter of transmitter must be smaller than at the receiver side.

design parameters	**geometric loss/dB**			
	design 1		design 2	
	from	to	from	to
link range	1.3	8.2	-3.4	7.2
divergence angle	1.93	4.6	-10.5	-5.6
receiver aperture diameter	14.8	-5.2	10.4	-9.8
transmitter aperture diameter	-6	7.2	-2.9	10.3

Table 7. Results of geometric loss with design parameters.

4.1.2. Total attenuation

Total attenuation depends on attenuation resulted from hazy and rainy days and geometric loss. The attenuation in hazy days depends on visibility, while during rainy days it would be determined by rainfall rate. Visibility range changes with the quantity and density of particles, such as fog, haze and dust attached to air. The higher the density of these particles is, the less visibility is and total attenuation increases. The density of these particles is not fixed. It keeps varying with time and place as well as rainfall. The quantity and density of these particles are unpredictable, and visibility and rainfall rate are also uncontrollable. Thus, they are all not part of FSO design.

We can control the value of geometric loss, because it depends on fixed parameters such as transmitter diameter and receiver apertures, transmission range, and beam divergence. During the design of FSO system, geometric loss must be at minimum to reduce the effect of total attenuation on FSO system. In this part, we used design 2 as demonstrated in Table 6 to calculate total attenuation because this design geometric loss is less as described above in Section 4.1.1.

4.1.2.1. Total attenuation during hazy days

Figure 15 shows total attenuation at low visibility. We used Eq. (8) to plot Fig. 15. Here, we assume that link range is 1 km. When visibility is 0.8 km, total attenuations are 31.8, 31 and 26.4 dB at wavelengths of 780, 850 and 1550 nm, respectively. And when visibility is 5 km, total attenuation are 16.8, 16.4, and 15.4 dB for wavelengths of 780, 850 and 1550 nm, respectively. It is suggested that the more visibility is the least effects of total attenuations on FSO performance.

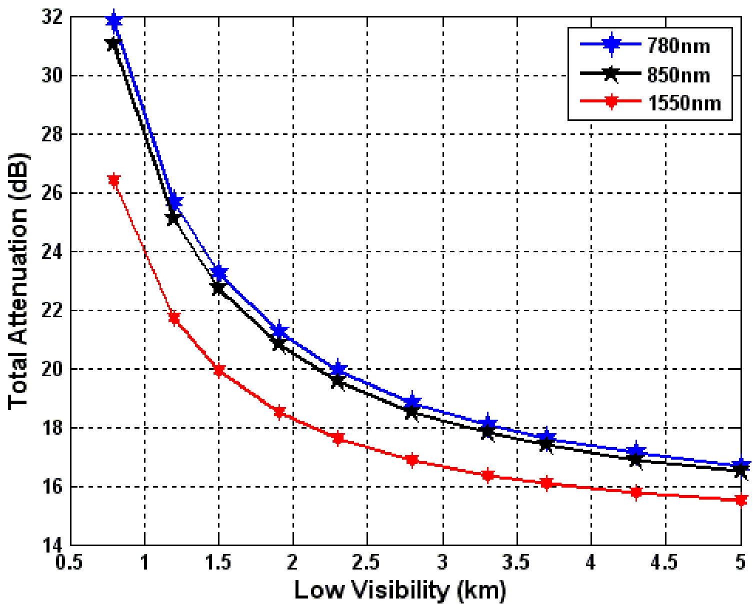

Figure 15. Total attenuation (dB) versus low visibility (km).

Figure 16 indicates the total attenuation versus average visibility. When visibility is 6.4 km, total attenuation is 15.96, 15.8 and 14.9 dB at wavelengths of 780, 850 and 1550 nm, respectively. Note that when visibility is 9.7 km, total attenuation are of 15.39, 15.28 and 14.7 dB at wavelengths of 780, 850 and 1550 nm, respectively. Based on the previously mentioned, we conclude that total attenuation at wavelength 1550 nm is less than that at wavelengths of 780 and 850 nm. Therefore, to reduce the effect of total attenuation during hazy days, we use the wavelength of 1550 nm.

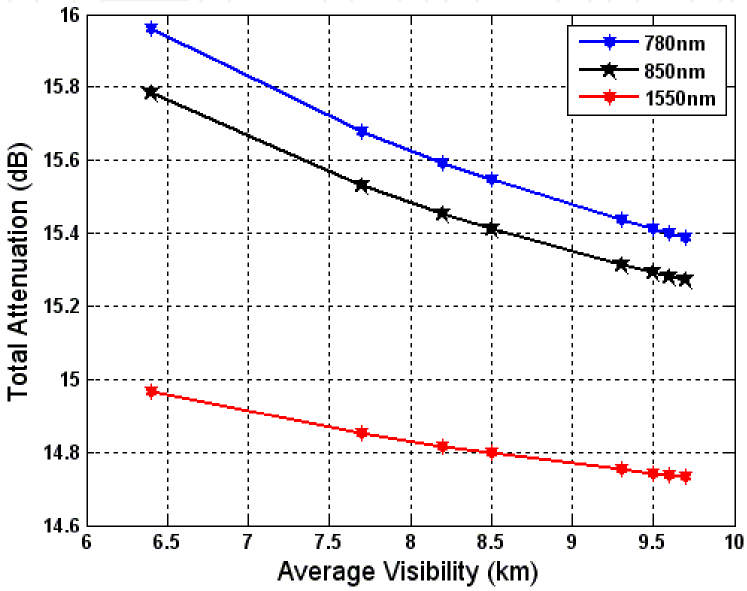

Figure 16. Total attenuation (dB) versus average visibility (km).

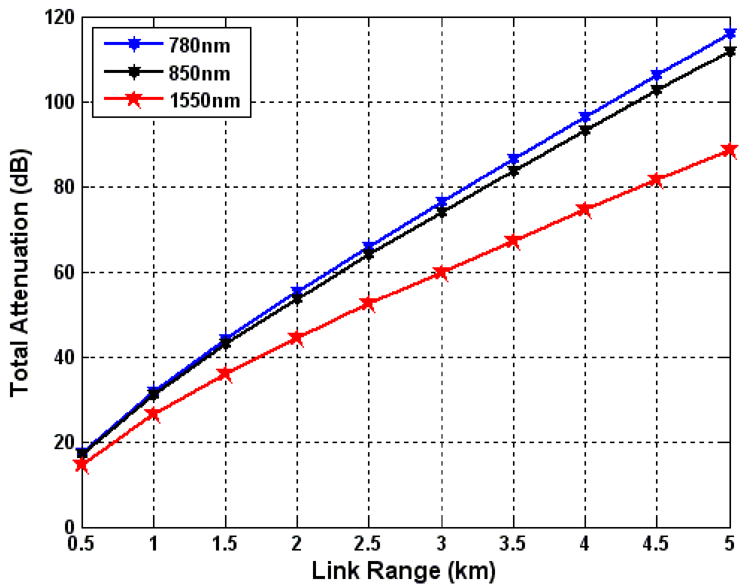

Figure 17. Total attenuation (dB) versus link range (km).

Figure 17 represents total attenuation versus link range. From this figure, we found that total attenuation directly proportions with link range. When link range is 0.5 km, total attenuation is 17.3, 16.9 and 14.6 dB at wavelengths of 780, 850 and 1550 nm, respectively. In addition, when link range is 5 km, total attenuation becomes 115.0, 111.8 and 88.4 dB at wavelengths of 780, 850 and 1550 nm, respectively. Therefore, to reduce the effect of total attenuation on FSO, the distance between the transmitter and receiver shall be small. Figure 18 shows the relationship between total attenuation and laser beam divergence for three wavelengths. With increasing the beam divergence, the total attenuations are increased for three cases as demonstrated in Fig. 18.

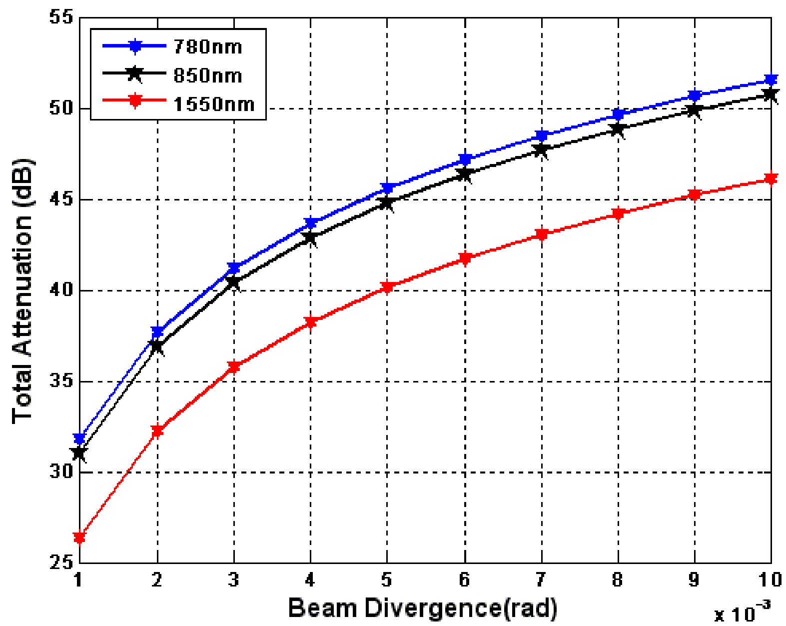

Figure 18. Total attenuation (dB) versus laser beam divergence (mrad).

That means when the beam divergence at 1 mrad the total attenuations 32, 31, and 26 for wavelengths 780, 850, and 1550 nm, respectively. While at beam divergence of 10 mrad, we noticed that the total attenuation was increased 51.1, 50.8, and 46 dB for three previously indicated wavelengths. Therefore, to reduce atmospheric attenuation, the beam divergence should be small in accordance with the previous results. Table 8 shows the results of total attenuation for design parameters at hazy days.

4.1.2.2. Total attenuation in rainy days

Figure 19 shows the total attenuation versus rainfall rate. It can be seen obviously that the influence of attenuation on transmission of FSO systems is more prominent during heavy rainfall compared to moderate and light rainfall. Figure 20 indicates the total attenuation versus link range. The atmospheric attenuation is proportional to link range, which showed

parameters	wavelength	total attenuation/dB	
		from	to
low visibility	780 nm	31.8	16.8
	850 nm	31	16.4
	1550 nm	26.4	15.4
average visibility	780 nm	15.96	15.3
	850 nm	15.8	15.3
	1550 nm	14.9	14.7
link range	780 nm	17.3	115
	850 nm	16.9	111.8
	1550 nm	14.6	88.4
beam divergence	780 nm	32	51.6
	850 nm	31	50.8
	1550 nm	26	46

Table 8. Results of total attenuation for design parameters at hazy days.

that when the link range increases, the total attenuation would increase as well. The results of total attenuation for design parameters at rainy days are presented in Table 9.

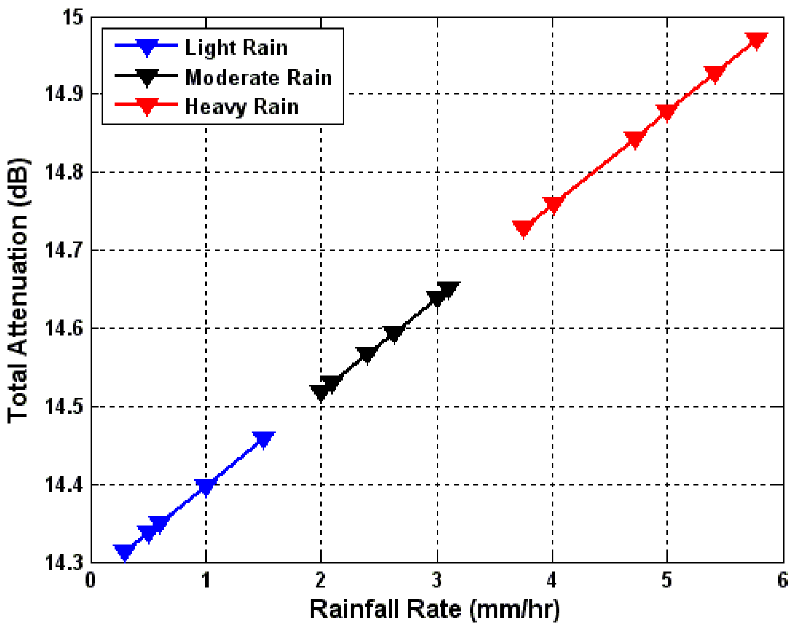

Figure 19. Total attenuation (dB) versus rainfall rate (mm/hr).

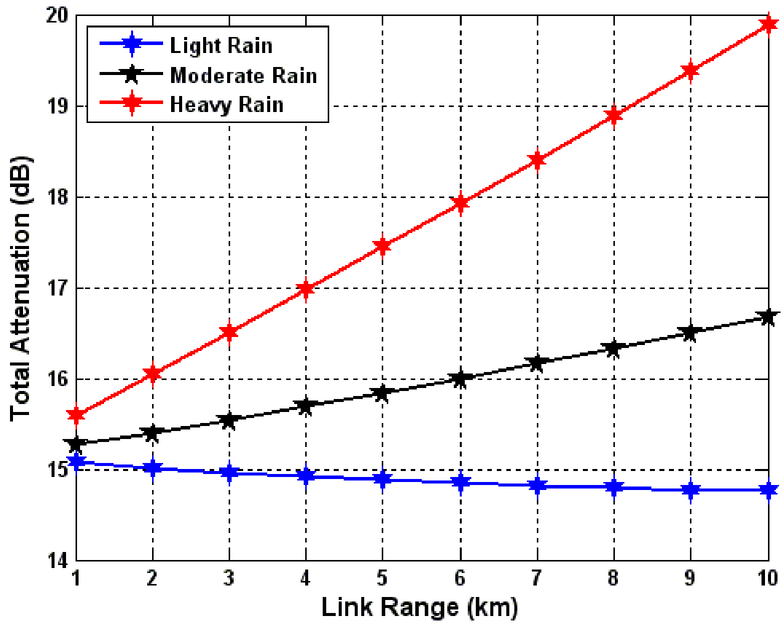

Figure 20. Total attenuation (dB) versus link range (km).

	rainfall	total attenuation/dB	
		from	**to**
rainfall rate	light	14.3	14.46
	moderate	14.5	14.67
	heavy	14.71	14.98
link range	light	15.1	15.5
	moderate	15.4	16.8
	heavy	15.6	20

Table 9. Results of total attenuation for design parameters at rainy days parameters.

4.2. Simulation results and discussion of haze effects on FSO in Sana'a, Aden, and Taiz cities

In this section, we study the effect of atmospheric attenuation and scattering coefficient on the performance of FSO system in environment of Sana'a, Aden and Taiz cities.

4.2.1. Sana'a city

Low visibility range for Sana'a city in Fig. 21 extends from 0.3 to 6 km. Scattering coefficient at low visibility of 0.3 km is 11.37, 10.99 and 8.69 km^{-1} for wavelengths of 780, 850 and 1550 nm, respectively. The scattering coefficient of 6 km low visibility is 0.45, 0.41 and 0.21 km^{-1} for wavelengths of 780, 850, and 1550, respectively.

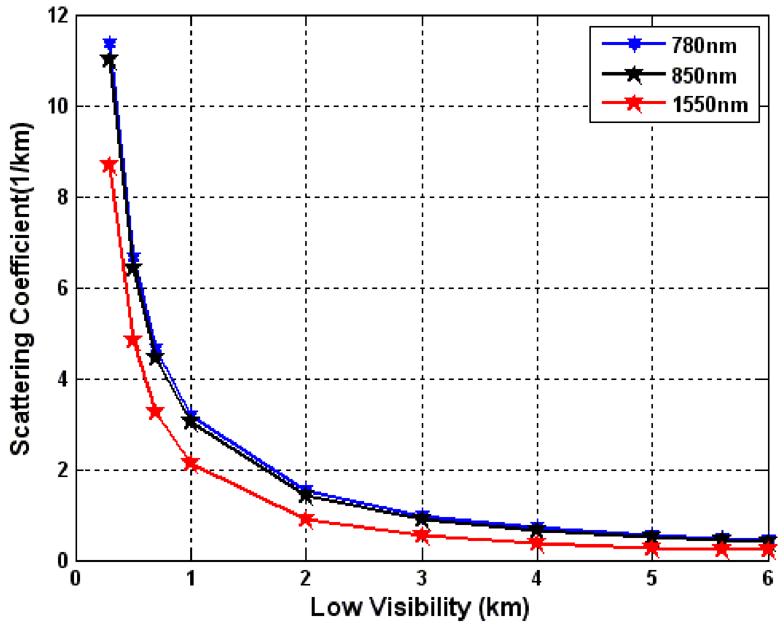

Figure 21. Scattering coefficient (km^{-1}) versus low Visibility for Sana'a city (km).

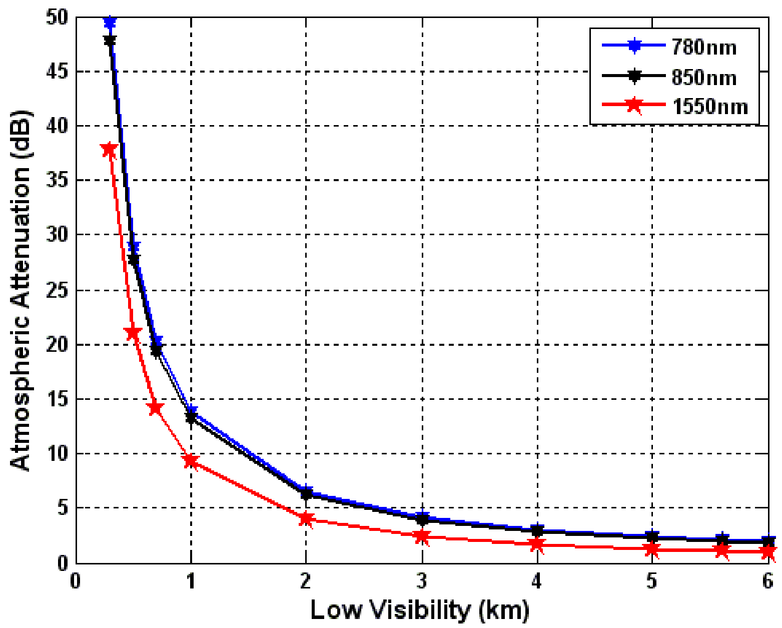

Figure 22. Atmospheric attenuation (dB) versus low visibility (km) for Sana'a City.

Figure 22 shows that the atmospheric attenuation versus low visibility in Sana'a city. At low visibility of 0.3 km, atmospheric attenuation is 49.4 dB, 47.7 dB and 37.7 dB for wavelengths of 780, 850 and 1550 nm, respectively. For 6 km low visibility, the atmospheric attenuation is about 2 dB, 1.8 dB and 0.94 dB for wavelengths of 780, 850 and 1550 nm, respectively.

4.2.2. Aden city

Low visibility range in Fig. 23 extends from 0.05 to 6 km for Aden city. Scattering coefficient at low visibility 0.05 km is 44.8, 43.8 and 37.6 km^{-1} for wavelengths of 780, 850 and 1550 nm, respectively. The scattering coefficient of 6 km low visibility is 0.45, 0.41 and 0.22 km^{-1} for wavelengths 780, 850, and 1550 nm, respectively.

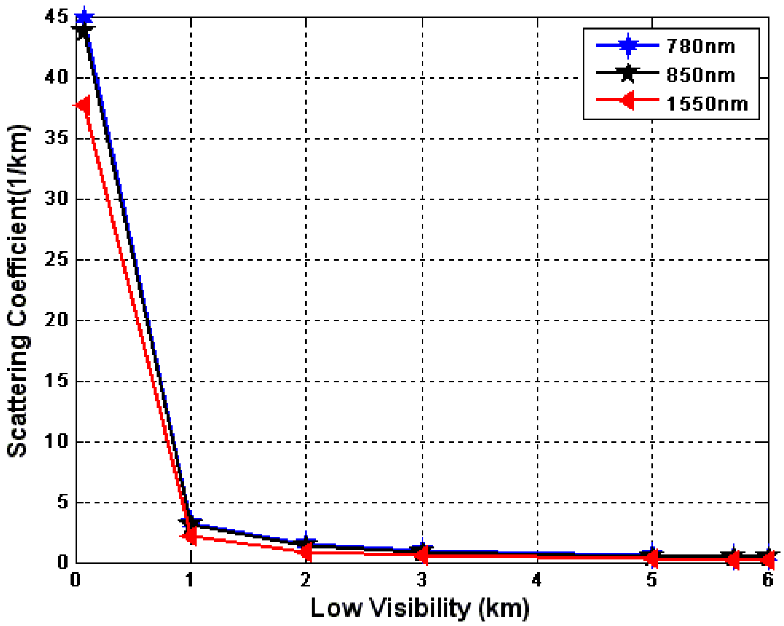

Figure 23. Scattering coefficient (km^{-1}) versus low visibility (km) for Aden city.

Figure 24 shows that the atmospheric attenuation versus low visibility for Aden city. At low visibility of 0.05 km, atmospheric attenuation is 194.4, 190.2 and 163.5 dB for wavelengths 780, 850 and 1550 nm, respectively. For 6 km low visibility, the atmospheric attenuation is about 1.95, 1.8 and 0.94 dB for wavelengths of 780, 850 and 1550 nm, respectively.

4.2.3. Taiz city

Low visibility range in Fig. 25 extends from 0.05 to 4 km for Taiz city. Scattering coefficient at low visibility 0.05 km is 44.8, 43.8 and 37.6 km^{-1} for wavelengths of 780, 850 and 1550 nm, respectively. The scattering coefficient of 4 km low visibility is 0.7, 0.65 and 0.37 km^{-1} for wavelengths of 780, 850, and 1550 nm, respectively. Figure 26 shows that the atmospheric attenuation versus low visibility for Taiz city. At low visibility of 0.05 km, atmospheric attenuation is 194.4, 190.2 and 163.5 dB for wavelengths of 780, 850 and 1550 nm, respectively. For 4 km low visibility, the atmospheric attenuation is about 3.1, 2.8 and 1.6 dB for wavelengths of 780, 850 and 1550 nm, respectively. Table 10 shows the results of scattering coefficient and atmospheric attenuation at low visibility for Sana'a, Aden and Taiz Cities. The results show

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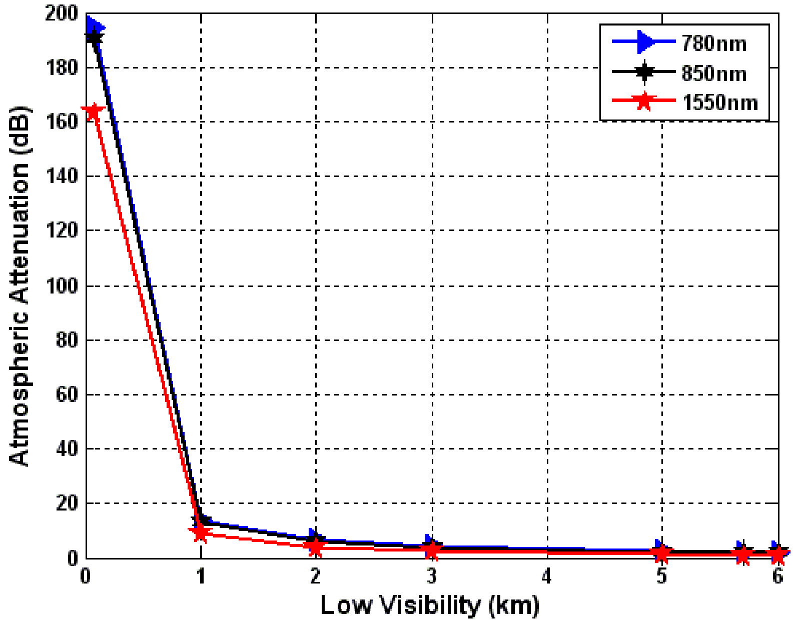

Figure 24. Atmospheric attenuation (dB) versus low visibility (km) for Aden city.

that with increasing the wavelength, in consequence the scattering coefficient and atmospheric attenuation decreased for the three cases were studied in this paper.

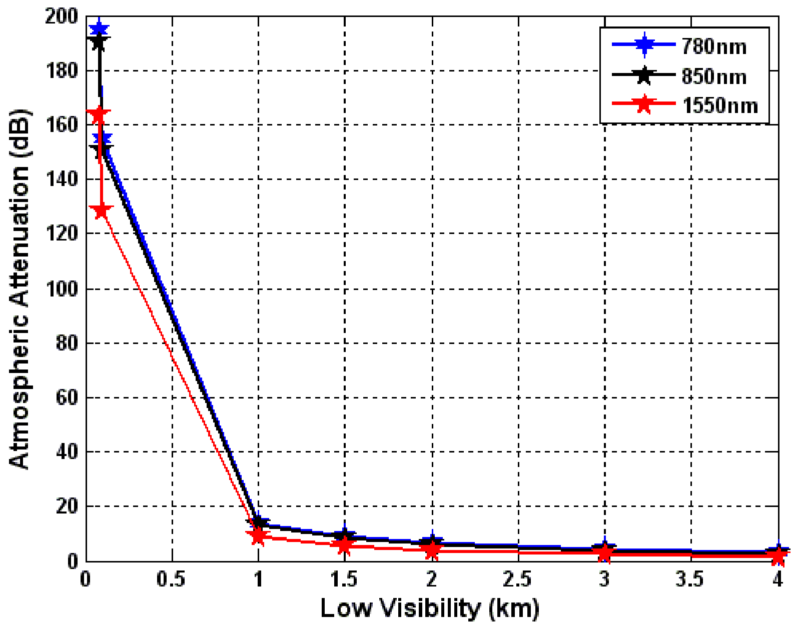

Figure 25. Scattering coefficient (km^{-1}) versus low versus low visibility (km) for Taiz city.

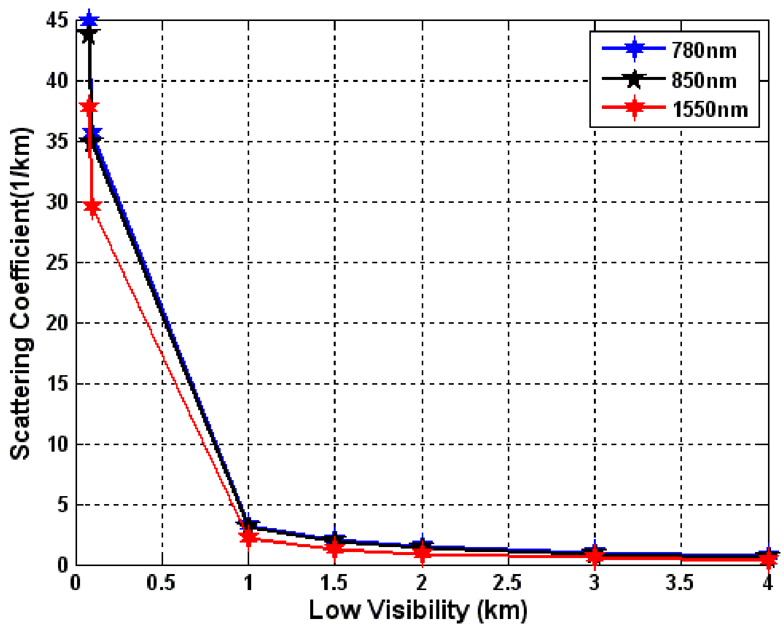

Figure 26. Atmospheric attenuation (dB) versus low visibility (km) for Taiz city.

city	wavelength	scattering coefficient/km^{-1}		atmospheric attenuation/dB	
		from	to	from	to
Sana'a	780 nm	11.37	0.45	49.4	2
	850 nm	10.99	0.41	47.7	1.8
	1550 nm	8.69	0.21	37.7	0.94
Aden	780 nm	44. 8	0.45	194.4	1.95
	850 nm	43.8	0.41	190.2	1.8
	1550 nm	37.6	0.22	163.5	0.94
Taiz	780 nm	44.8	0.7	194.4	3.1
	850 nm	43.8	0.65	190.2	2.8
	1550 nm	37.6	0.37	163.5	1.6

Table 10. Results of scattering coefficient and atmospheric attenuation at low visibility for Sana'a, Aden and Taiz cities.

5. Optical link budget

After illustrating the geometric loss, total attenuation, and haze effects on the FSO in Sana'a, Aden and Taiz cities, we return to the link budget of FSO systems. This section concentrates on received power versus low and average visibility, and link range. Table 11 illustrates the

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main FSO link parameters. We note that all the given values in the following table are presumed to calculate the received power for three cases as presented in Figs. 27–29.

parameters	description
wavelength (λ)	780, 850, 1550 nm
transmit power (P_{tx})	23.52 dB
beam divergence	1 mrad
visibility	5 km

Table 11. Optical link budget parameters.

The results presented in Fig. 27 show the relationship between received power for three different wavelengths and low visibility. As seen in Fig. 27, received power increases with the increment of low visibility. We note that the obtained received power at the wavelength of 1550 nm is the best as compared to the other two. For example, the received power curve for the wavelength of 1550 nm increases from −67 dBm at the distance of 0.6 km to –27 dBm at the distance of 5 km. However, we note that the receiving power is reduced for other two wavelengths of 780 and 850 nm. As shown in Fig. 28, the received power at wavelength of 1550 nm shows the best compared to other two wavelengths. While the received powers at the wavelengths of 780 and 850 nm are, lower.

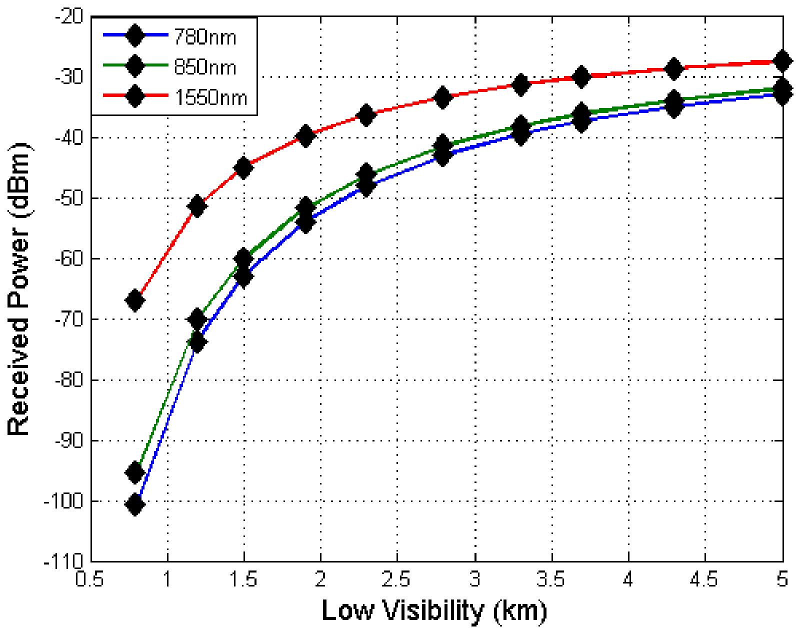

Figure 27. Received power (dBm) versus low visibility (km).

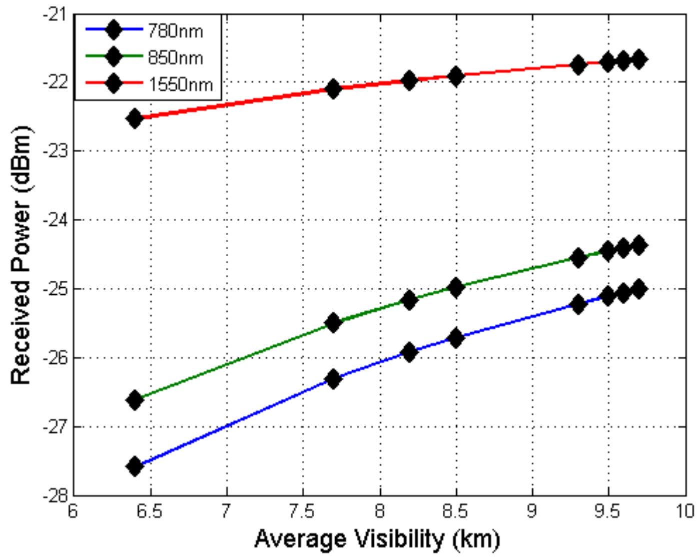

Figure 28. Received power (dBm) versus average visibility (km).

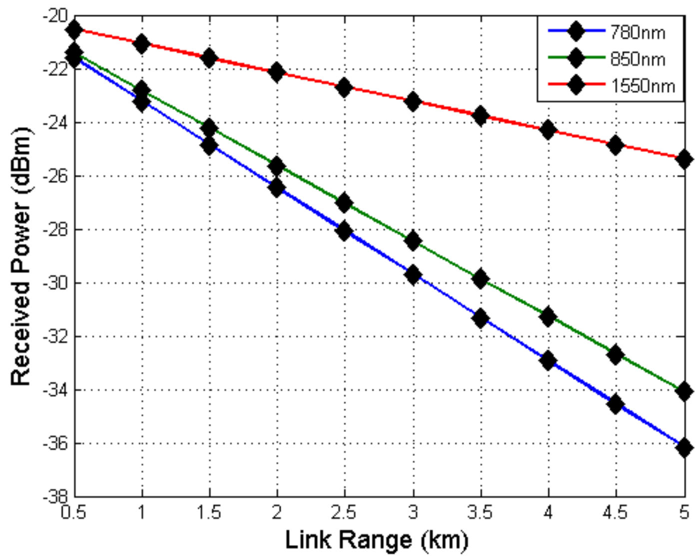

Figure 29. Received power (dBm) versus link range (km).

Figure 29 shows the received power versus the link range. As the link range between transmission and receiver increases, the received power decreases. At the distance of 0.5 km, the received power for the wavelength of 1550 nm is of –20.3 dBm where for the others two are of –21.7 dBm. However, in the distance of 5 km, the received power reaches –36 dBm for wavelength of 780 nm and –34.1 dB for the wavelength of 850 nm. For three study cases, the study was done to improve the efficiency of FSO systems, the wavelength of 1550 nm for three cases must be used and the distance between transmitter and receiver should be reduced.

6. Simulation results of BER and SNR

The data was taken from the Civil Aviation and Meteorology Authority and the Yemeni Meteorological Service. The work includes the analysis of these real data. The purpose here is to discuss the relationship for calculating the variance, SNR, and BER for a range of parameters. We used the wavelengths of 850, 1000, and 1550 nm. Particular attention was given to the 1550 nm wavelength since it is commonly used as the 3rd window of optical communication backbone links. Moreover, being significantly bigger than visible wavelengths, the human retina in particular and the components of the eye in general are less sensitive to the 1550 nm wavelength. Thus, this wavelength is appropriate for eye safety.

Figure 30 illustrates the log intensity fluctuations versus the link range between transmitter and receiver for three values of wavelengths. The log intensity fluctuation depends on the wavelength and increases with the propagation distance. As the transmission range increases the variance (atmospheric turbulence) increases too. For a 2000 m transmission range, the variance is about 0.17 for the wavelength of 850 nm, 0.12 for 1000 nm, and 0.075 for 1550 nm. For a 4000 m transmission range, the variance is about 0.56 for 850 nm, 0.42 for 1000 nm, and 0.25 for 1550 nm. These results show that the use of a wavelength of 1550 nm can reduce the variance "atmospheric turbulence" effect on the FSO systems [37].

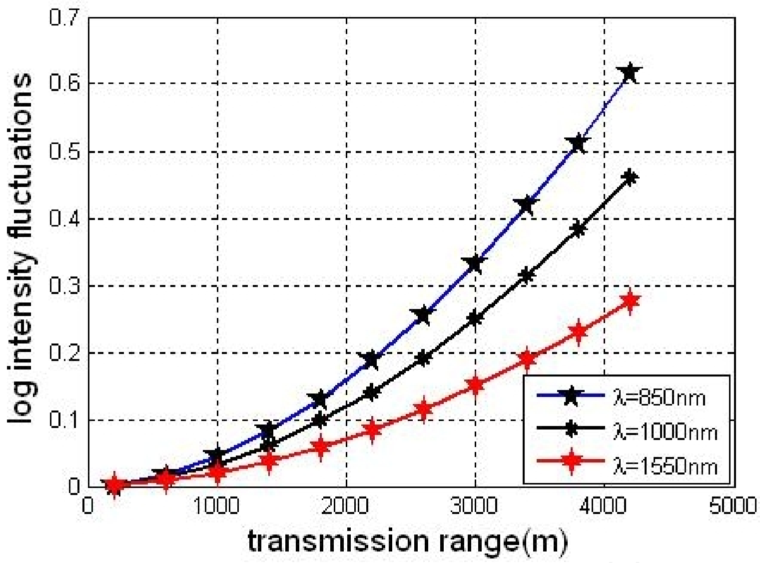

Figure 30. Intensity fluctuations against transmission range.

Figure 31 indicates the comparison between the beam spreading on a distance l from the transmitter in case of atmospheric turbulence and in case without atmospheric turbulence. The spot size of the beam at the transmitter (with the distance $l = 0$) equals 0.008 m. At the distance 200 m, the spot size of the beam is ω (l) = 0.015 m in case of absent turbulence and ω_{eff} (l) = 0.015 m in case of turbulences. At the distance 5000 m, the ω (l) = 0.31 m and ω_{eff} (l) = 0.33 m. From the above results, we conclude that the expansion of the spot size of the beam depends on the distance between sender and receiver as indicated on Fig.32, and on the atmospheric turbulence along the transmission range as indicated on Fig. 33. The higher the turbulence is, the greater the expansion of the beam size is. Figure 34 shows the SNR versus the transmission range of 0 to 4500 m. As the link range between the transmitter and receiver increases, the SNR decreases. This means that the increment of link range is able to decrease the transmission quality and efficiency of FSO systems. At a low range of 200 m, the SNR is about 74 dB for 850 nm, 77 dB for 1000 nm, and 82 dB for 1550 nm. For 4000 m, the SNR is about 18 dB for 850 nm, 21 dB for 1000 nm, and 26 dB for 1550 nm.

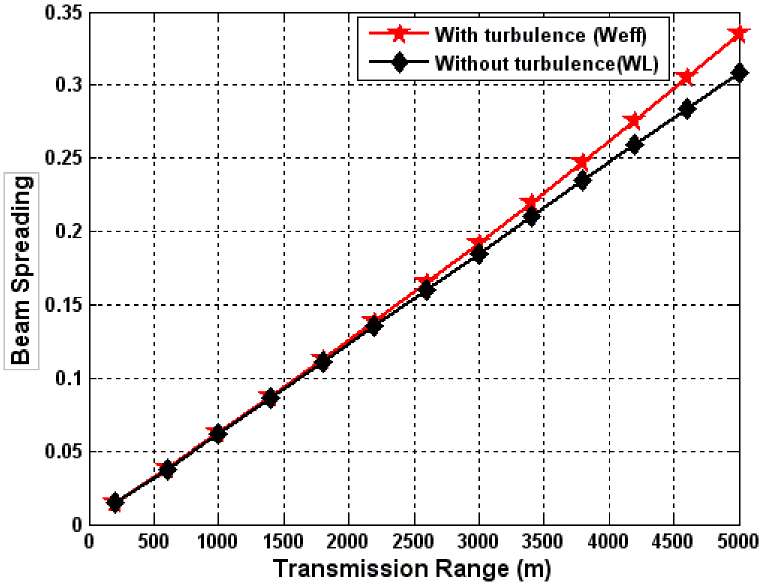

Figure 31. Beam spreading versus transmission range.

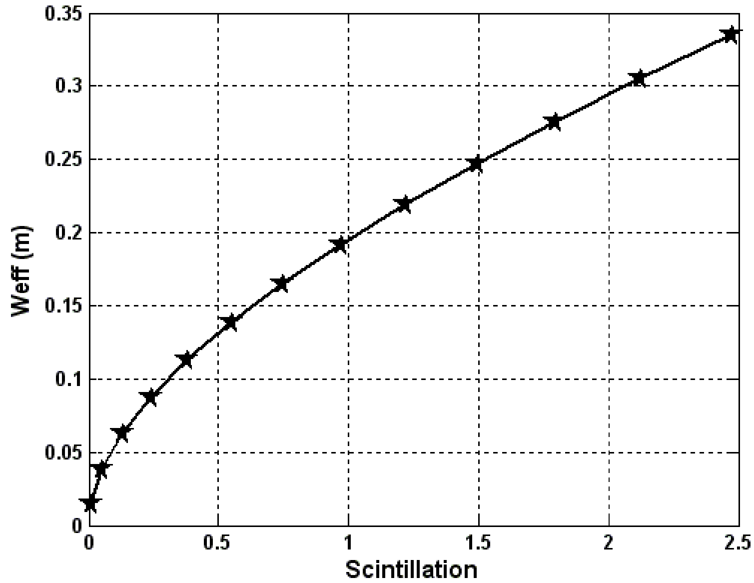

Figure 32. Waist of beam with turbulence versus scintillation.

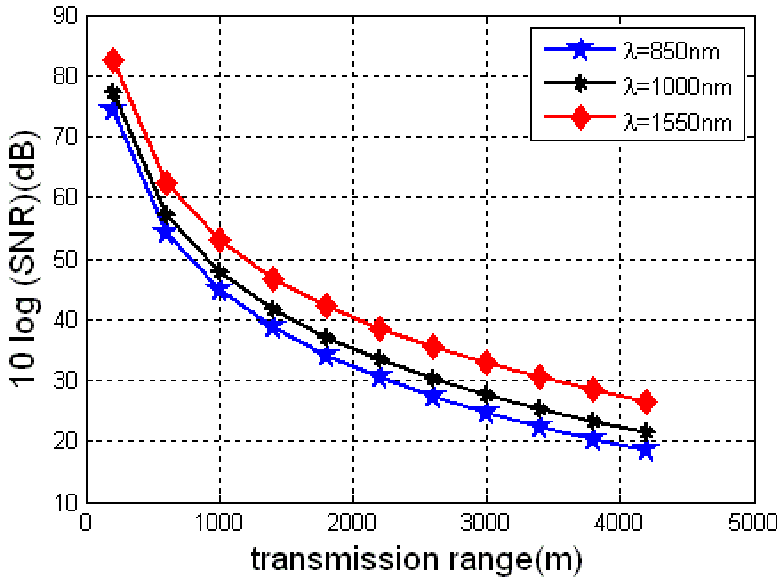

Figure 33. SNR versus transmission range.

Figure 34 shows the BER versus the transmission range. As the link range between transmission and receiver increases, the BER increases too. At 2500 m link range, the BER is about 10^{-4} for 850 nm, 10^{-6} for 1000 nm, and 10^{-9} for 1550 nm. At 4000 m, the BER is 10^{-2} for 850 nm, 10^{-3} for 1000 nm, and 10^{-4} for 1550 nm. If we want an acceptable communication BER of 10^{-9}, the maximum link range between transmitter and receiver should be about 1600 m for 850 nm, 1900 m for 1000 nm, and 2500 m for 1550 nm.

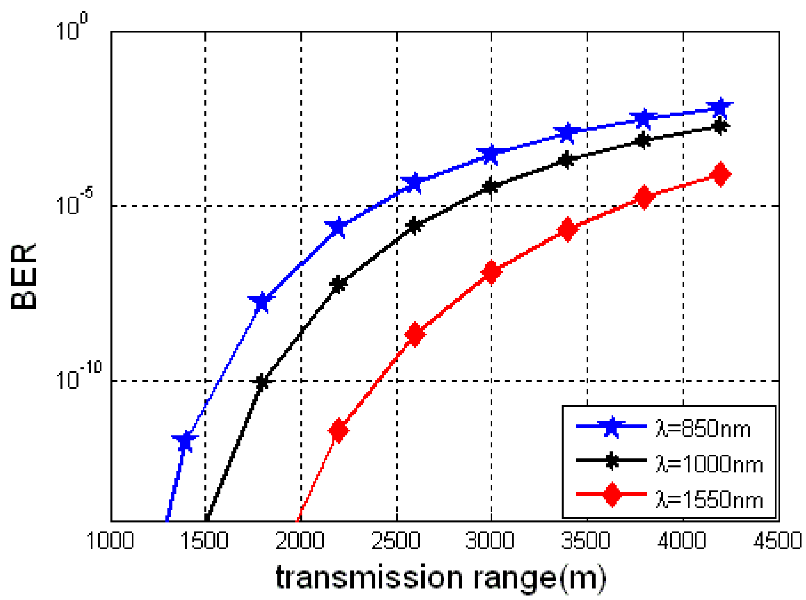

Figure 34. BER versus transmission range.

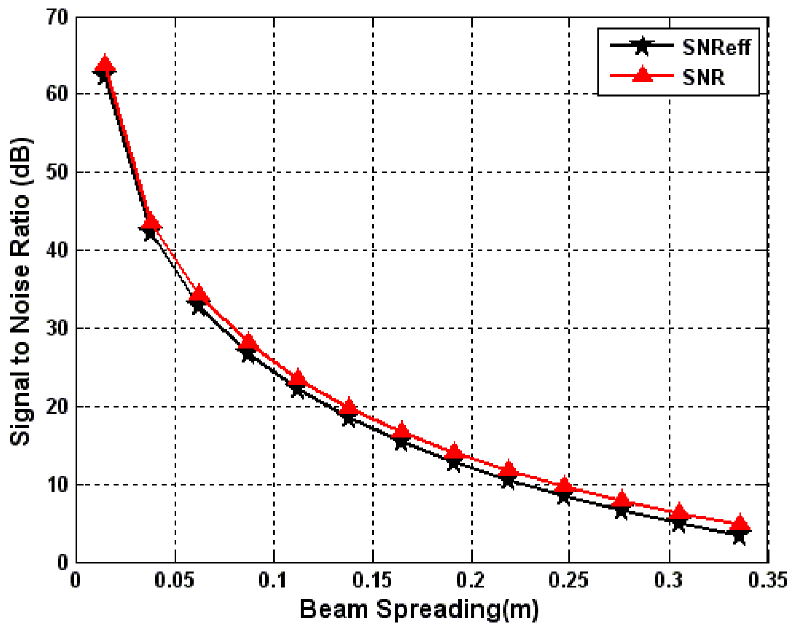

Figure 35. SNR with and without turbulence, SNR_{ref} and SNR, respectively, versus transmission range.

Figure 35 indicates SNR versus expansion of the beam size resulting from air turbulence. For a beam size of ω_{eff} (l) = 0.015 m, the SNR = 64 dB and SNR_{eff} = 62 dB, but for ω_{eff} (l) = 0.33 m, the SNR = 4.7 dB and SNR_{eff} = 3.4 dB. From these results, we conclude that when the beam expands, the loss in terms of the beam intensity increases. This leads to the decrease in the SNR value, and therefore the BER increases as indicated in Fig. 36. For a spot size of 0.015 m, the BER = 10^{-115}, and when the spot size of the beam is 0.33 m, the BER increases up to 10^{-5} approximately. From the results above, we conclude that the narrow beam shows a limited effect of the atmospheric turbulence on the intensity.

Figure 37 shows the BER versus link range between transmitter and receiver. This figure graphically represents the BER as a function of the irradiance variance. For 3500 m, BER is 10^{-6} for the SNR and 10^{-5} for the SNR_{eff}. For an irradiance variance 0.05 the BER 10^{-6} for the SNR and 10^{-5} for the SNR_{eff}. From the results obtained, we conclude that to improve the performance of the FSO transmission systems, it is recommended to shorten the link range between transmitter and receiver. Another improvement of the signal quality offered by the FSO systems includes using the 1550 nm wavelength. The SNR of FSO systems with 1550 nm wavelength is higher than that corresponding to 1000 and 850 nm wavelengths. To reduce the atmospheric turbulence effects on FSO systems, we suggest using the 1550 nm wavelength. Moreover, for the 1550 nm wavelength, the allowable power is largely higher compared to smaller wavelengths (about 50 times compared to 850 nm). This shows that the system operates well during heavier attenuation of the atmosphere since we can safely increase power at the source.

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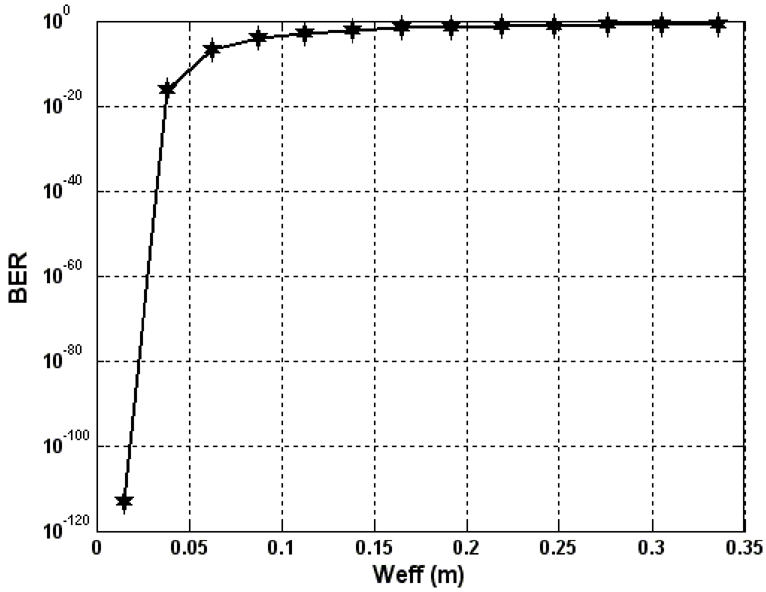

Figure 36. BER versus waist of beam with turbulence.

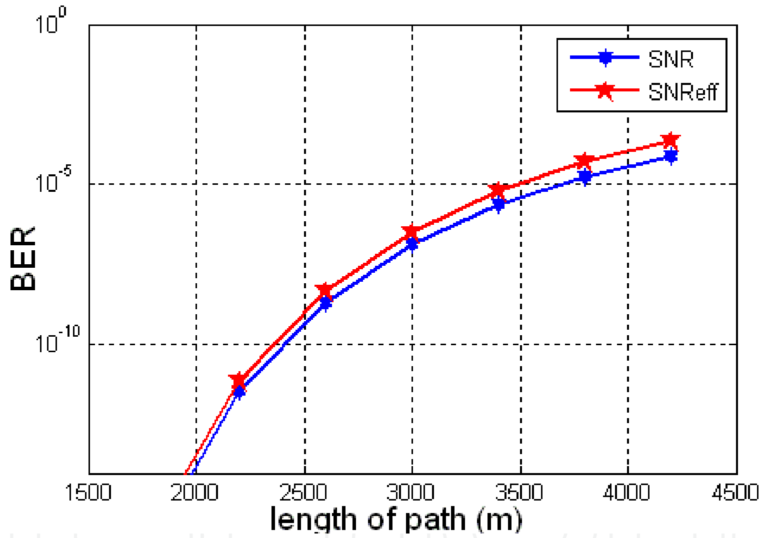

Figure 37. BER versus transmission range for SNR and $SNR_{eff.}$

7. Summary

Recently, telecommunication and computer networking are moving toward optics communication. Because the light is the hasten medium to transmit, the huge information, it's cost effective, flexibility, quick deployment, and the promise of optical bandwidth.

FSO is considered as alternative choice that can be employed as a reliable solution to broadband short distance applications. However, mobile operators are planning to use this technology to short distance links. In this chapter, we briefly introduced the concepts of FSO technology, mathematical approach of this technique. Practical part, we take the climate effects for deployment of FSO in Yemeni territorial as a case study. We have studied in detail the total attenuation influencing FSO systems. The total attenuation in this case study depends on two parameters: scattering and geometric losses. This work was concentrated on two different designs as demonstrated in Table 6. These results showed that when the link range, divergence angle, and transmitter aperture were increasing, the geometric loss increased too. But, we found that geometric loss decreased with the increasing of the receiver aperture diameter. Total attenuation also increased with increasing of the distance link, low visibility, and with decreasing of the wavelength. It was also shown that the effect of rainfall on the FSO system performance was so small that we can neglect it. In general, FSO performance was bad in Taiz at the low visibility compared to Sana'a and Aden. However, in the average visibility, the FSO performance was effective in three cities.

We concentrate on the scintillation effects on the performance of FSO links. The analysis was carried out for the variance, SNR, and BER in the environment of Yemen. Scintillation for the Yemeni environment is wavelength and distance dependent. The wavelength of 1550 nm turned out to be interesting since it is less sensitive to atmospheric turbulence and harmless to the human eye. The results indicate that the performance of the FSO system is good during the worst conditions in Yemen. To improve the transmission efficiency of FSO systems, the wavelength of 1550 nm must be used and the distance between transmitter and receiver must be reduced. To achieve a BER of 10^{-9} during air turbulence, the distance between transmitter and receiver should be 2600 m. Thus, the FSO system may be applied in Yemeni territorial efficiently even in case of the presence of air turbulence.

8. Important questions related to this chapter for self-evaluation:

1. What is free-space optical communication?
2. What is the maximum speed can FSO products offer?
3. What are the operating wavelengths of FSO systems?
4. What are the FSO technology applications?
5. Do you need a license to operate FSO system?
6. What are the advantages and disadvantages of FSO technology?
7. What is the recommended distance of the FSO link?
8. What is the different between FSO and fiber-optics?
9. Is FSO safe for eyes and human body?
10. Is FSO transmission secure?
11. Can FSO systems operate through windows glass?
12. Is the sunlight influence on FSO link?

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13. What about the climate effect on FSO performance?
14. In figure 5, what is meant by free space and how to calculate its losses?
15. Physically, discuss the Beer`s law.
16. Calculate the antenna gain for FSO product if the wavelength is 1550 nm?
17. What is meant by divergence angle?
18. How to connect the FSO links to the network?
19. Is FSO characterized as cost effective and why?
20. Is FSO only deployed on rooftops?
21. What are the advantages of using infrared communication instead of other radio relay links line of sight (LOS)?
22. What are the transmitted power recommended for FSO products?
23. Could you design an FSO link and calculate the link budget?
24. Calculate the received power of FSO link demonstrated in figure 6?
25. What is meant by focal length?
26. If the observer is looking at a telecommunication tower of 20 meter high at a distance of 120 m and the distance between the optical center of the eye lens and fovea is of 17 mm.
    - **a.** Graphical represent of the eye looking at a tower.
    - **b.** calculate the size of retinal image of the tower (h) that's reflected primarily in the area of the fovea.

answer: h=2.83 *mm*

1. What happens if a bird or an micro airplane flies through the transmitted beam?
2. Using MATLAB, Could you write the code of figure 33 and display all the curves?
3. What is meant by BER, MSE, SNR, and PSNR?
4. Is FSO technology suitable to transmit information from the earth to the satellite?

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