

Free Space Optics (FSO)-Past, Present, Future and Mathematical Models of Atmospheric Turbulence for FSO Link Budget Analysis

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Abstract:-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.

Keywords:-Free-space optical communications, link budget, turbulence, fading, absorption, scattering, scintillation

I. INTRODUCTION

Free-space optical communication (FSO) systems (in space and inside the atmosphere) have developed in response to a growing need for high-speed and tap-proof communication systems. Links involving satellites, deep-space probes, ground stations, unmanned aerial vehicles (UAVs), high altitude platforms (HAPs), aircraft, and other nomadic communication partners are of practical interest. Moreover, all links can be used in both military and civilian contexts. FSO is the next frontier for net-centric connectivity, as bandwidth, spectrum and security issues favour its adoption as an adjunct to radio frequency (RF) communications [2].

While fixed FSO links between buildings have long been established and today form a separate commercial product segment in local and metropolitan area networks [2], the mobile and long-range applications of this technology are aggravated by extreme requirements for pointing and tracking accuracy because of the small optical beam divergences involved. This challenge has to be addressed to fully exploit the benefits of optical links. Furthermore, long-haul optical links through the atmosphere suffer from strong fading as a result of index-of-refraction turbulence (IRT) and link blockage by obscuration such as clouds, snow and rain.

In this paper an overview of the challenges a system designer has to respond to when implementing an FSO system is provided. Typical gains and losses along the path from the transmitter through the medium, to the receiver are introduced in this paper. Unlike radio and microwave systems, free space optical communications requires no spectrum licensing and interference to and from other systems is not a concern. In addition, the point-to-point laser signal is extremely difficult to intercept, making it ideal for covert communications. Free space optical communications offer data rates comparable to fiber optical communications at a fraction of the deployment

cost while extremely narrow laser beam widths provide no limit to the number of free space optical links that may be installed in a given location.

The fundamental limitation of free space optical communications arises from the environment through which it propagates. Although relatively unaffected by rain and snow, free space optical communication systems can be severely affected by fog and atmospheric turbulence. Free Space Optics are additionally used for communications between spacecraft. The optical links can be implemented using infrared laser light, although low-data rate communication over short distances is possible using LEDs. Maximum range for terrestrial links is in the order of 2-3 km, but the stability and quality of the link is highly dependent on atmospheric factors such as rain, fog, dust and heat. Amateur radio operators have achieved significantly farther distances (173 miles in at least one occasion) using incoherent sources of light from high-intensity LEDs. However, the low-grade equipment used limited bandwidths to about 4 kHz. In outer space, the communication range of free-space optical communication is currently in the order of several thousand kilometres, but has the potential to bridge interplanetary distances of millions of kilometres, using optical telescopes as beam expanders.

Free space optical communication has attracted considerable attention recently for a variety of applications. Because of the complexity associated with phase or Frequency modulation, current free-space optical communication systems typically use intensity modulation with direct detection (IM/DD). Atmospheric turbulence can degrade the performance of free-space optical links, particularly over ranges of the order of 1 km or longer. Inhomogeneities in the temperature and pressure of the atmosphere lead to variations of the refractive index along the transmission path. This index inhomogeneities can deteriorate the quality of the received

image and can cause fluctuations in both the intensity and the phase of the received signal. These fluctuations can lead to an increase in the link error probability, limiting the performance of communication systems. Aerosol scattering effects caused by rain, snow and fog can also degrade the performance of free-space optical communication systems but are not treated in this paper.

The objective of this paper is to study different conditions of atmosphere so as to minimize the different losses taking place when light signal passes through free space.

II. PAST, PRESENT and FUTURE

Optical Communication, in various forms, have been used for thousands of years. The Ancient Greeks polished their shields to send signals during battle. In the modern era, semaphores and wireless solar telegraphs called Heliographs were developed, using coded signals to communicate with their recipients.

In 1880 Alexander Graham Bell and his then-assistant Charles Sumner Tainter created the photo phone, in Washington, D.C. Bell considered it his most important invention. The device allowed for the transmission of sound on a beam of light. On June 3, 1880, Alexander Graham Bell conducted the world's first wireless telephone transmission between two building rooftop sits. First practical use came in military communication systems many decades later.

The invention of lasers in the 1960s revolutionized Free Space Optics. Military organizations were particularly interested and boosted their development. However the technology lost market momentum when the installation of optical fiber networks for civilian uses was at its peak.

In 1966 Charles K. Kao and George Hockham proposed optical fibers at STC Laboratories (STL), Harlow, when they showed that the losses of 1000 db/km in existing glass (compared to 5-10 db/km in coaxial cable) was due to contaminants, which could potentially be removed.

Optical fiber was successfully developed in 1970 by Corning Glass Works, with attenuation low enough for communication purposes (about 20dB/km), and at the same time GaAs semiconductor lasers were developed that were compact and therefore suitable for transmitting light through fiber optic cables for long distances.

After a period of research starting from 1975, the first commercial fiber-optic communications system was developed, which operated at a wavelength around 0.8 μm and used GaAs semiconductor lasers. This first-generation system operated at a bit rate of 45 Mbps with repeater spacing of up to 10 km. Soon on 22 April, 1977, General Telephone and Electronics sent the first live telephone traffic through fiber optics at a 6 Mbps throughput in Long Beach, California.

The second generation of fiber-optic communication was developed for commercial use in the early 1980s, operated at

1.3 μm , and used InGaAsP semiconductor lasers. Although these systems were initially limited by dispersion, in 1981 the single-mode fiber was revealed to greatly improve system performance. By 1987, these systems were operating at bit rates of up to 1.7 Gb/s with repeater spacing up to 50 km.

The first transatlantic telephone cable to use optical fiber was TAT-8, based on Desurvire optimized laser amplification technology. It went into operation in 1988. Third-generation fiber-optic systems operated at 1.55 μm and had losses of about 0.2 dB/km. They achieved this despite earlier difficulties with pulse-spreading at that wavelength using conventional In GaAsP semiconductor lasers. Scientists overcame this difficulty by using dispersion-shifted fibers designed to have minimal dispersion at 1.55 μm or by limiting the laser spectrum to a single longitudinal mode. These developments eventually allowed third-generation systems to operate commercially at 2.5 Gbit/s with repeater spacing in excess of 100 km.

The fourth generation of fiber-optic communication systems used optical amplification to reduce the need for repeaters and wavelength-division multiplexing to increase data capacity. These two improvements caused a revolution that resulted in the doubling of system capacity every 6 months starting in 1992 until a bit rate of 10 Tb/s was reached by 2001. Recently, bit-rates of up to 14 Tbit/s have been reached over a single 160 km line using optical amplifiers.

In the late 1990s through 2000, industry promoters, and research companies such as KMI and RHK predicted vast increases in demand for communications bandwidth due to increased use of the Internet, and commercialization of various bandwidth-intensive consumer services, such as video on demand. Internet protocol data traffic was increasing exponentially, at a faster rate than integrated circuit complexity had increased under Moore's Law.

III. THEORY

Free Space Optics (FSO) systems are generally employed for 'last mile' communications and can function over distances of several kilo meters as long as there is a clear line of sight between the source and the destination, and the optical receiver can reliably decode the transmitted information.

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.

FSO link is demonstrated as in Fig. 1. 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.

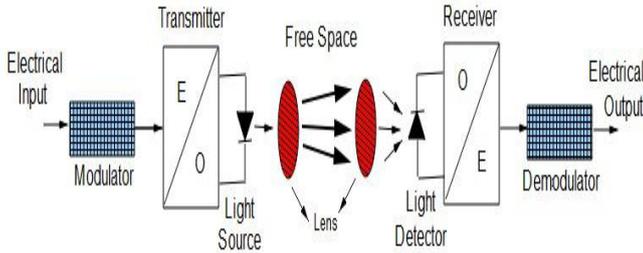


Figure 1. Block diagram of an optical wireless link showing the front end of an optical transmitter and receiver.[3]

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 (1) illustrates the data rate of FSO system:

$$Data\ Rate \left[\frac{bits}{sec} \right] = \frac{1}{\eta} P_r \left[\frac{photons}{sec} \right] \quad (1)$$

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. 2.

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

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

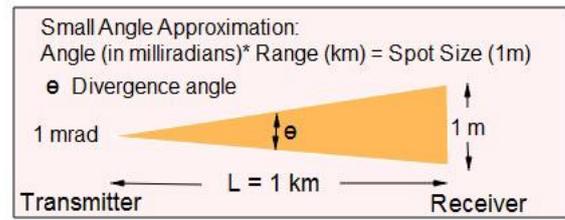


Figure 2. Small angle- divergence and spot size between transmitter and receiver.[3]

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).

Table 1. The divergence, range, and spot diameter

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

IV. MATHEMATICAL MODEL OF ATMOSPHERIC TURBULANCE

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.

1.1 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 [3].

Table 2: Radius ranges for various types of particles.

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
Clod	1 to 10	100 to 300
Raindrops	10 ² to 10 ⁴	10 ⁻⁵ to 10 ⁻²
Snow	10 ³ to 5x10 ³	N/A

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) [3, 4].

1.2 Visibility Runaway 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 [5]. 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 [6].

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

$$V = \frac{I_{Max} - I_{min}}{I_{Max} + I_{min}} \quad (2)$$

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 [6].

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 [8].

1.3 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 [4]:

$$\tau = \exp(-\beta L) \quad (3)$$

Where,
 τ is the atmospheric attenuation;
 β is the total attenuation coefficient and given as

$$\beta = \beta_{abs}\beta_{scat} \quad (4)$$

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.

1.3.1 Absorption

Absorption is caused by the beam’s photons colliding with various finely dispersed liquid and solid particles in the air such as water vapour, dust, ice, and organic molecules. The aerosols that have the most absorption potential at infrared wavelengths include water, O₂, O₃, and CO₂ Absorption has the effect of reducing link margin, distance and the availability of the link [10].

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 [6], which allows specific frequencies of light to pass through it.

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 [5].

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

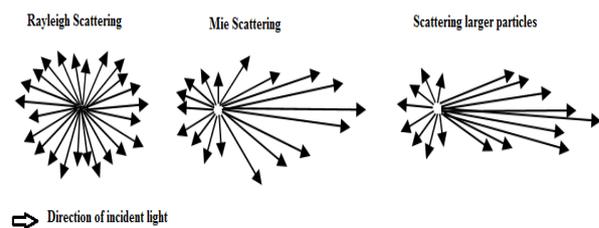


Figure 3. Patterns of Rayleigh, Mie and Non-selective scattering. [15]

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 [14]. If $x_0 \ll 1$, the backward lobe becomes larger and the side lobes disappear as shown in Fig. 3 [15] 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. 3 and then it is Mie scattering. For $x_0 \gg 1$, the particle presents a large forward lobe and small side lobes that start to appear as shown in Fig. 3 [15] 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 (3) [16]. It is possible to calculate the scattering coefficients from the concentration of the particles and the effective cross section such as [11]:

Table 3: Typical atmospheric scattering parameters, with size parameter.

Type of particle	Radius (μm)	Size parameter (X_0)	Scattering
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

1.4 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 [23,24]. 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 iso-phase surface [24]. The refractive index can be described by the following relationship [24]:

$$n - 1 \approx 79 \times \frac{P}{T} \quad (5)$$

Where:

P : is the atmospheric pressure in [mbar] .

T : is the temperature in Kelvin [K] .

If the size of the turbulence eddies are larger than the beam diameter, the whole laser beam bends, as shown in Fig. 4. If the sizes of the turbulence eddies are smaller than the beam diameter and so the laser beam bends, they become distorted as in Fig. 5. 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. 5.

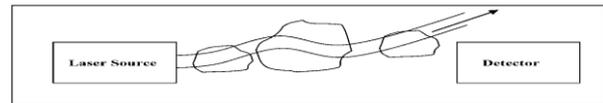


Figure 4. Laser beam wander due to turbulence cells that are larger than the beam diameter.

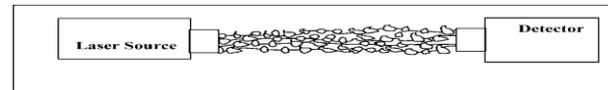


Figure 5. Scintillation or fluctuations in beam intensity at the receiver due to turbulence cells that is smaller than the beam diameter.

1.4.1 Refractive index structure

Refractive index structure parameter C_n is the most significant parameter that determines the turbulence strength. Clearly, C_n depends on the geographical location, altitude, and time of day. Close to ground, there is the largest gradient of temperature associated with the largest values of atmospheric pressure (and air density). Therefore, one should expect larger values C_n 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 [8]. In applications that envision a horizontal path even over a reasonably long distance, one can assume C_n to be practically constant. Typical value of C_n for a weak turbulence at ground level can be as little as $10^{-17} \text{ m}^{-2/3}$, while for a strong turbulence it can be up to $10^{-13} \text{ m}^{-2/3}$ or larger.

1.4.2 Scintillation

Scintillation may be the most noticeable one for FSO systems. Light travelling 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 [8,9]:

1.4.3 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.

1.5 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 eq. 6:

$$\frac{P_r}{P_t} = \frac{d_2^2}{[d_1 + (L\theta)]^2} \times \exp(-\beta L), \quad (6)$$

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. (6), 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 [24].

1.6 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 greater 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 eq.7.

$$P_r = P_t + G_{Tx} + G_{Rx} - \text{total loss} \quad (7)$$

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

$$L = \frac{P_t A_r T_1 T_2}{2\pi P_{rm} (1. \cos \phi)} \quad (8)$$

Here, P_t represent the optical output power from the transmitter (in mW), A_r is the active area of the photo detector, 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 ϕ 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.

V. CONCLUSION

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 travelled 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.

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