LINE OF SIGHT FREE SPACE OPTICAL COMMUNICATIONS LINK

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ABSTRACT

Free space optical communication FSO links have several features that make them attractive because they supply equip high bandwidth, high bit rates, low bit error rates, low cost, security, and it is a reliable communication medium. However, the greatest challenge for FSO communications link originates from the fundamental characteristics of free space channel; tackling these challenges requires a detailed understanding of the factors affecting optical signal propagation through free space. The aim of this paper is to provide detailed analysis of the effect of different parameters of FSO communication line of sight LOS link, including the effect of the coefficients of absorption, Rayleigh and Mie scattering, turbulence, and visibility on Propagation of Optical signal in free space for three selected types of optical sources namely Gallium Arsenide GaAs LED (850 nm), Nd:YAG solid state lasers (1060 nm), and InGaAsP laser diode (1550 nm). A numerical FSO channel model developed in MATLAB software is provided for estimating the influence of these parameters on propagation of optical signal through free space of the selected optical sources under various range and atmospheric conditions. The provided results indicate that the Rayleigh scattering is significant up to (λ=1µm), and it becomes negligible in IR band. In addition, it is proved that longer wavelength of InGaAsP laser diode (1550 nm) is less attenuated in comparison with shorter wavelengths of the other two sources.Consequently, the performance of the system at the wavelength of 1550 nm is much better than the wavelengths of 1060 nm and 850 nm.

Keywords: Keywords: Optical transmitter, Atmospheric optical channel, Rayleigh scattering, InGaAsP laser diode,Visibility.

الملخص

الاتصالات البصرية في الفضاء الحر (FSO) تمتاز بعدة عوامل تجعلها مناسبة و مرغوبة حيث توفر عرض نطاق ترددي عالي ، معدلات بت عالية ، معدلات خطأ بت منخفضة ، وتكلفة منخفضة، بالإضافة الي أنها تعتبر وسيلة اتصال أمنة وموثوقة. ومع ذلك ، فإن التحدي الأكبر لهذا النوع من الاتصالات يكمن في الخصائص الأساسية لقناة الفضاء الحرة ؛ ولمعالجة هذه التحديات فانه يتطلب فهماً مفصلاً للعوامل التي تؤثر على انتشار الإشارات الضوئية عبر الفضاء الحر. الهدف من هذا البحث هو تقديم تحليل مفصل لتأثير عوامل مختلفة على انتشار الإشارة البصرية في الفضاء الحر لخط اتصال هذه الأنظمة ، بما في ذلك تأثير معامل الامتصاص ، كلا من تشتت رايلي (Rayleigh scattering) و تشتت مي (Mie scattering) ، الاضطراب، والرؤية. ولهذا الغرض فقد تم اختيار ثلاثة مصادر ضوئية بأطوال موجية مختلفة وهي Gallium Arsenide GaAs LED (850 nm) ، وليزر الحالة الصلبة Nd:YAG lasers (1060nm) ، و InGaAsP laser diode (1550 nm). تم استخدام برنامج MATLAB لحساب مدى تأثير هذه البارامترات على انتشار الإشارة البصرية عبر الفضاء الحر للمصادر الضوئية المختارة عند مسافات و ظروف جوية مختلفة. تشير النتائج المقدمة إلى أن تشتت رايلي يكون مهما حتى (λ = 1nm) ، ويصبح ضئيلًا في مدى الأطوال الموجية لأشعة تحت الحمراء. بالإضافة إلى ذلك ، ثبت أن الطول الموجي الأطول لـ InGaAsP laser diode (1550 nm) أقل توهينًا مقارنةً بالأطوال الموجية الأقصر للمصدرين الآخرين . بالنتيجة يكون أداء و فاعلية النظام عند الطول الموجي 1550 نانومتر أفضل بكثير من الأطوال الموجية 1060 نانومتر و 850 نانومتر.

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الكلمات المفتاحية : المرسل البصري، القناة البصرية، تشتت رايلي، InGaAsP ليزر دايود، مجال الرؤية.

1. INTRODUCTION

A Free Space Optical Link FSO is a transmitter-receiver pair that sends information between two points using modulated light (typically a laser or an LED). This provides many attractive features of FSO such as high bandwidth capability, low probability of interception, very secure due to the high directionality and narrowness of the beam, installation is easier and fast, and the cost is moderate, low bit error rates, license-free band of operation, and impermeable signal for radio frequency interference or regulation. In FOS communication link there is no need for a physical transmittance medium between the points, only line of sight (LOS). FSO systems work well in most conditions, but suffers dramatic performance losses under several atmospheric parameters such absorption, scattering, and turbulence. The choice of wavelengths for FSO communication has to be eyes and skin safe as certain wavelengths between 400 nm to 1500 nm can cause possible eye hazards or retina damage [1]. In generally, the wavelength that used for all commercially available FSO communication systems conventionally is (785 nm), (850 nm), and (1550 nm). However, the physics and transmission properties of optical beam as it penetrates the atmosphere are similar in both near infrared and visible wavelength bands. FSO communications systems consist three components; an optical transmitter to send of signal through the atmosphere, a free space transmission channel often containing (gases, cloud, smoke, rain, fluctuations in temperature, aerosol and fog) causing the transmitted optical signal to be attenuated, and optical receiver for processing the obtained signal.

FSO links have wide range of applications including their uses in ground stations, satellites, deep space probes, unmanned aerial vehicles (UAVs), aircraft, high altitude platforms, and other nomadic communications partners are of practical interest. Moreover, all links can be used in both civilian and military contexts.

Finally, this technology appears to have very high growth prospects in the future especially after much progress has been made in FSO communication. Lots of commercial FSO ground and space link products are already available in the market, and we hope in the near future that this technology will bring worldwide telecommunication revolution in this field.

We will briefly focus on concept of FSO communications scenarios in section 1. Section 2 presents a the principal components of FSO communication link including optical transmitter, atmospheric optical channel, and optical Receiver are described in detail and this section provides the description of various challenges imposed by propagation of optical beam through FSO channel. In section 4 we describe the configuration scenario for direct LOS link. Finally, a mathematical model for calculating the effect of atmospheric scattering, visibility, and divergence on the transmission of an optical signal in e free space is presented in section 5.

2. FREE SPACE OPTICAL COMMUNICATION SCENARIOS

FSO communication systems are where free space for successful transmission of optical signals serves as a communication channel between transceivers that are line-of-sight (LOS). The channel can be atmosphere, space, or vacuum, whose characteristics determine the transmission and reception of optical signals in order to design effective and efficient communication systems. Depending on the various scenarios for developing optical connections, point-to-point, multipoint-to-point, point-to-multipoint, and multipoint-to-multipoint FSO communications are feasible.On this basis, the applications of these systems are classified into terrestrial and space optical links that include building-to-building, ground-to-satellite, satellite-to-ground, satellite-to-satellite, satellite-to-airborne platforms (unmanned aerial vehicles (UAVs) or balloons), [2]–[3] etc. The classification of the FOC system is illustrated in Fig.1.

Performance of FSO systems depends on two main factors. The first factor is system design, where the designer has only control over the system design. The second factor is the weather conditions under which these systems will operate. Where performance of these systems can be expected only within a certain distance and can be modeled mathematically. However, it is very difficult to predict weather conditions with high accuracy especially when unexpected things happen like fires, volcanic eruptions, etc.

Fig.1. Typical application scenarios of FSO system [4].

2.1 FSO Advantages

The advantages of FSO are described below:

- Great bandwidth to cost ratio.
- Very secure because of the narrowness and high directionality of the beam.
- Provide high bandwidth links over short distances.
- License free operation.
- High Bandwidth.
- Not effected by electromagnetic interference.
- Full Duplex operation.
- Low bit error rates
- No Fresnel zone necessary only direct line of sight.

2.2 FSO Disadvantages

The disadvantages of FSO are as following:

- Mounting - The optical source requires a very fixed installation site which makes it unsuitable for tower and mast mounting.
- Limited life.
- It can be affected by atmospheric weather conditions, fog, rain, smoke etc. Snow can build up on improperly installed units.

3. THE PRINCIPAL COMPONENTS OF FSO SYSTEM

The basic functional components of FSO communication system consists of:

1. Optical transmitter (Lasers or LEDs).
2. Atmospheric optical channel.
3. Optical receiver (PIN or APD).

In optical transmitter system, the data signal to be transmitted is modulated with light signal by optical modulator. The transmitter optic transmits this modulated signal to the receiver through the free space channel. In receiver unit, the receiver optic received the transmitted signal. This signal is detected and filtered by the potodetector and low pass filter, respectively. Finally, an estimate of the transmitted data signal is obtained. The generalized fundamental block diagram of a point-to-point FSO link is shown in Fig.2.

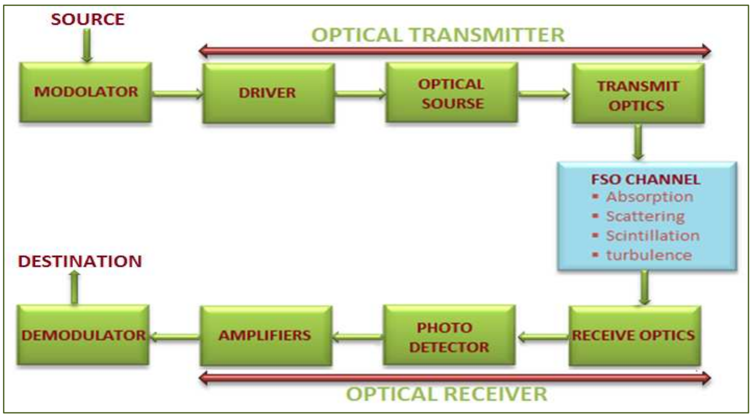

Fig.2. Basic block diagram of a point-to-point FSO link [5].

The schematic representation of a point-to-point FSO link between the optical transmitter and the optical receiver is visualized in Fig.3. The FSO transmitter, located on first building and connected to a local area network (LAN) situated in that building, transmits the optically modulated signal through the free space. The transmitted signal is received by the FSO receiver located in second Building and attached to a LAN located in that building as well.

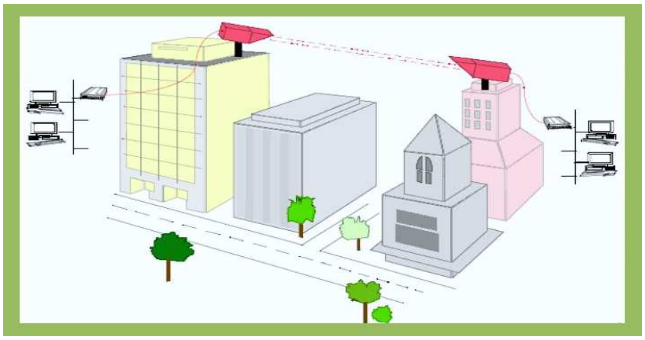

Fig.3. Schematic of a point-to-point FSO link between the transmitter and receiver.

3.1 Optical Transmitter

The optical transmitter converts the source information into optical signals which are transmitted to the optical receiver through the atmosphere. Optical transmitter operates by modulating a source of light that is typically generated by laser or light emitting diode (LEDs).The basic components of the transmitter are modulator, driver circuit for the optical source to stabilize the optical beam against temperature fluctuations, and collimator that collects, collimates, and directs the optical signals to the optical receiver through atmospheric channel. Block diagram of the optical transmitter is shown in Fig.4.

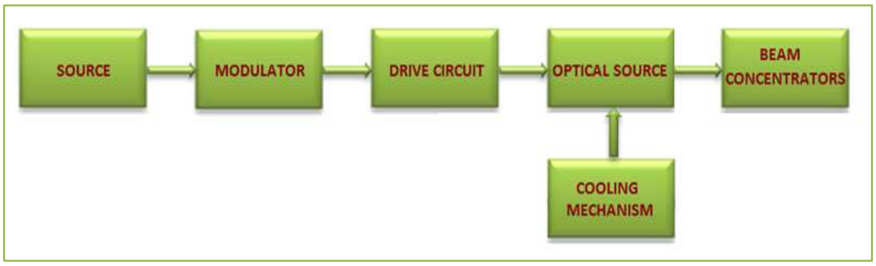

Fig.4. Block diagram of optical transmitter.

When choosing the type of light source to be used, the designer must take into account several different factors such as, data rate, eye safety, and the distance between the transmitter and the receiver. The selection of laser source for FSO applications depends on various factors. It is important that the transmission wavelength is correlated with one of the atmospheric windows. Good atmospheric windows are around 850 nm and 1550 nm in SWIR wavelength. In LWIR spectral range, some wavelength windows are present between 3-5µm (especially 3.5-3.6µm), and 8–14 µm [6]. At present the availability of suitable light sources in these longer wavelength ranges is very limited. Additionally, most sources require lower temperature cooling, which limits their use in commercial communication applications.

In addition, some of the key requirements which influence the choice of the transmitter signal for FSO-based applications are Pulse repetition frequency , pulse width, output beam quality, average output power, beam pointing stability, pulse extinction ratio, mass and size, and operational lifetime.

3.1.1 Nd: YAG Laser

Neodymium yttrium aluminium garnet (Nd: YAG) Solid-state lasers which operates at 1064 nm wavelength are Suitable for long- range FSO applications in the defence and securities sector. Nd: YAG laser can generate very high peak power approximately (100's MW), short duration (usually ns) pulses with good beam efficiency. This allows the signals to propagate and be detected over long distances. This laser is adequate to transmit immense amount of power and is used in coherent systems with highly stable Nd: YAG oscillator [7]. Nd:YAG laser has many applications in illuminators and range finders etc. When using this type of laser, care must be taken because it has a harmful effect on the eyes.

3.1.2 Laser Diodes

Laser diodes LD are used in free space optical communication and inter- satellite links, and their beam does not spread while covering longer distances also they , they often have higher frequencies, which increases the modulation rate and the overall communication rate. LDs have faster rise and fall times which improve the switching speed and over all throughput of the system. LDs which have operating wavelength centered at 850 nm, 1060 nm, and 1550 nm are typically favored for FSO systems. Table 1 gives the compounds involved in the lasers source which are commonly used for FSO systems [8].

Table 1. Compounds used in lasers in FSO [9]

Operating Wavelength (nm)	Semiconductor material
620-895	$Ga_{(1-x)}Al_{(x)}As$
904	GaAs
890-980	InGaAs
1100-1650	$In_{(1-x)}Ga_{(x)}As_{(y)}P_{(1-y)}$
1550	$In_{(0.58)}Ga_{(0.42)}As_{(0.9)}P_{(0.1)}$
1604	$Nd^{3+}:Y_3Al_5O_{12}$; $Nd^{3+}:YVO_4$;$Nd^{3+}YLiF_4$

3.1.3 Light Emitting Diode LEDs

In recent years, LEDs have been developed as novel transmitters for visible light based FSO communications. These LEDs, which have lateral dimensions of less than (100 μm), have very high modulation bandwidths (which have been reported to exceed 800 MHz) which is enabled by their small feature size, which in turn supports high wireless data transmission rates. Two parameters, namely the differential carrier lifetime and the resistance-capacitance (RC) time constant, determine the modulation bandwidth of LEDs. Table 2 shows a comparison of various high-power LEDs which are commonly used for FSO systems.

Table 2. Compounds used LEDs in FSO.

Operating Wavelength (nm)	Compound(s)
550	GaP
585-595	GaAsP:N
590	AlAs
605-620	GaAsP
630-660	GaAsP
770-870	AlGaAs
850-940	GaAs
930	InP
1100-1670	InGaAsP

Both LDs and LEDs have weaknesses and strengths when it comes to FSO communications. LDs have higher optical power output and can switch faster, but LEDs are cheaper, simpler, and more confident. Though the coherence and minimal divergence of LDs is optimal for optical fiber communication systems, it does not play as big a role in wireless optical communication. Additionally, though LDs can switch faster, LEDs can switch quick enough for our application (>=1 MHz). Since the goal is to have a cheap, small, reliable communication system that at least can handle (1 MHz), LEDs were chosen as the photon source for the optical transmitter.

Table 3 shows the Comparison of LEDs and LDs.

Table 3. Comparison of LEDs and Laser Diodes

Characteristic	LED	Laser Diode
Optical Spectral Width	25-100 nm	0.01 to 5 nm
Modulation Bandwidth	<200 MHz	> 1 GHz
Minimum Output Beam Divergence	Wide (about 0.5^{o})	Narrow (about 0.01^{o})
Temperature Dependency	Little	Very temperature dependent
Special Circuitry Required	None	Threshold and temperature compensation circuitry
Cost	Low, off-the-shelf	High, need specialized optics

	components available	and electronics
Lifetime	Long, with little degradation of power levels	Medium, power levels degrade over time
Reliability	High, 10^8 hours	Moderate, 10^5 hours
Coherence	Incoherent	Coherent
Eye Safety	Eye safe	Must take precautions

3.2

Atmospheric Optical Channel

The performance of FSO communication link is significantly influenced by the ambient conditions between the optical transmitter and the optical receiver, due to the optical nature of the FSO. Thus, because of many processes, the optical signal emitted by the emitter will be attenuated before it reaches the optical electronic receiver. To determine the optical transmission from a transmitter to a receiver, there are three primary processes that affect the optical beam: absorption, scattering, turbulence. The effect of these three factors is to reduce the amplitude of the transmitted optical signal that reaches the optical receiver through the atmosphere. In general, the first tow processes, absorption and scattering, are grouped together under the topic of extinction. Extinction is defined as the attenuation in the amount of optical signal passing through the atmosphere. The attenuation over a distance of *x* of the homogeneous atmosphere is given by:

$$\Phi = \Phi_0 e^{-\sigma x} \text{ [W]} \quad \text{………} 1$$

where σ is the extinction coefficient which is made up of two components:

$$\sigma = a + \gamma \quad [\text{km}^{-1}] \quad \text{………} 2$$

where *a* is the absorption coefficient and γ is the scattering coefficient [10].

3.2.1 Atmospheric Particulates

Particles of Atmospheric are often in the form of precipitation, but they are also encountered in the form of dust, smoke, and ash from volcanic eruptions and other pollutants.. System performance is affected by all types of severe weather due to the combination of dense particles and turbulence. The system performance also decreases with increasing particle density. As the fog has the largest influence on the performance of the optical signal. This is because the size of the water droplets in the fog is suitable for scatter wavelengths in the infrared spectrum [11].

3.2.2 Atmospheric Absorption

Absorption is fundamentally a quantum process where an atmospheric molecule absorbs the energy from an optical signal. Absorption changes the atmospheric molecule internal state, increasing its energy, and resulting in a temperature change. Each type of particle in the air has associated absorption strength. Particles responsible for the absorption can be classified into two groups: aerosol absorbers and molecular absorbers. Level at which the optical signal will decrease due to absorption is determined by both type and density of particles in the air.

Water vapor has a significant effect on absorption of near-IR wavelengths. Carbon dioxide is a strong absorber in the midwave IR, but the midwave band is superior for FSO sensor application in high humidity compared with longwave IR band.

Aerosol absorbers actually found present in the atmosphere are smoke, dust, from the deserts, volcanic ash and sea salt particles. Aerosols are often the result of many sources of pollution. The vast majority of aerosols occur over land, in the Northern Hemisphere, and within 1 km of the Earth's atmosphere [11].

A graph of typical atmospheric transmission is shown Fig.5. Specific absorption bands of water, carbon dioxide and oxygen molecules are indicated which restrict atmospheric transmission to several windows as summarized in table 4.

Table 4. Atmospheric windows

Name	wavelength range (µm)
Near Infrared NIR	0.75 - 1.1 µm
	1.1 - 1.35
Short wave Infrared SWIR	1.4 - 1.8
	2 - 2.5
Mid wave Infrared MWIR	3 - 4
	4.5 - 5
Long wave Infrared LWIR	8 - 9.5
	10 - 14

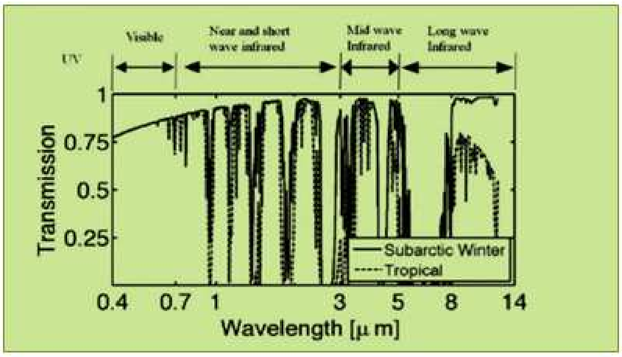

Fig.5. Typical atmospheric transmission for 1-km path length [10].

3.2.3 Atmospheric Scattering

The process of scattering is the resultant of photons colliding with atmospheric particles whereby the photon energy is reradiated in all directions. The fraction of the photon's energy extracted and the angular pattern that it is reradiated is a function of the relative atmospheric particle size to that of the incident photon wavelength. The scattering process for different scattering particles present in the atmosphere is summarized in Table 5 [12].

Table 5. Typical atmospheric scattering parameters, with size parameter.

Type of particles	Radius (µm)	Size parameter (Xo)	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

In general, the scattering modes are divided into three categories. These categories are based on the relationship between the wavelength of the incident photon and the particle size. These models are the

Raleigh scattering, Mie scattering, and Geometric optics. Fig.6 illustrates the patterns of Rayleigh, Mie and non-Selective scattering.

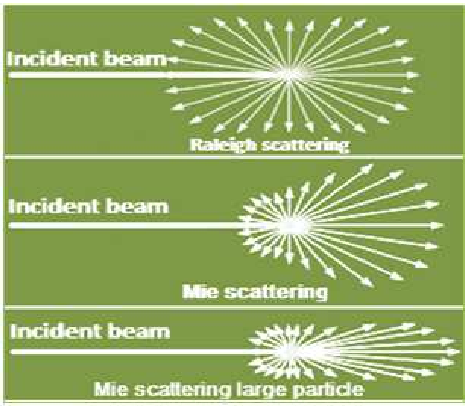

Fig.6. Typical angular scattering patterns [10].

The first form is the *Raleigh scattering*. It is used when the radius of the particle is approximately less than one-tenth of a wavelength. The scattering coefficient is proportional to λ^4. Raleigh scattering leads to the blue color of the sky. The blue wavelengths have a strong scattering interaction with the atmosphere. The blue is scattered in all direction so that the sky appears blue, where the red color of the Smoke and light mist particles are usually small with respect to wavelengths of IR radiation, and IR radiation can therefore penetrate more through smoke and mists than visible light radiation. However, fog, rain particles and aerosols are larger and, as a result, scatter IR and visible radiation to a similar degree. The attenuation of light due to Raleigh scattering is expressed as follows:

$$\Phi(x) = \Phi_0 e^{-\gamma x} \quad [\mathrm{W}], \quad \ldots 3$$

Where only the scattering coefficient γ is considered. Raleigh scattering coefficient is given by:

$$\gamma = \gamma_r N \quad [\mathrm{km}^{-1}], \quad \ldots\ldots. 4$$

Where N is the molecular number density, and γ_r is the Raleigh scattering cross-section which is given by:

$$\gamma_r = \frac{4 \cdot \pi^2 \cdot N \cdot V^2}{\lambda^4} \cdot \frac{(n^2 - n_0^2)^2}{(n^2 + 2n_0^2)^2} \cdot \sin^2 \phi \quad [10].. 5$$

Where:

N: number of particles per unit volume (cm^{-3}),
V: volume of scattering particle (cm^{-3}),
λ: wavelength of radiation,
n_0: refractive index of medium in which the particles are suspended,
n: refractive index of scattering particles ,
ϕ: scattering direction angle.

The second form is *Mie scattering* which happens when the wavelength is about the same size as the molecule. The attenuation given by Mie scattering is of the same form as Rayleigh scattering and is expressed as follows:

$$\Phi(x) = \Phi_0 e^{-\gamma_m x} \quad [\mathrm{W}] \quad \ldots 6$$

where γ_m is the aerosol attenuation coefficient. The aerosol attenuation coefficient is a function of the aerosol density and is related by:

$$\gamma_m = \frac{M(h)}{M(0)} \gamma_m(0) \quad [\mathrm{km}^{-1}], \quad \ldots\ldots\ldots 7$$

where *M(h)* denotes the aerosol density at a height *h*, and $\gamma_m(0)$ is the aerosol coefficient at sea level (density at sea level ~200 cm^{-3}) [13]. The aerosol coefficient also varies with wavelength. Table 6 gives the value of Rayleigh scattering coefficient γ and the aerosol attenuation coefficient γ_a at sea level with various wavelengths.

Another consequence of Rayleigh scattering varying as λ^4 is that for the light beam wavelengths of interest, the effect of Rayleigh scattering on the total attenuation coefficient is very small. Therefore, aerosol or Mie scattering dominates the total attenuation coefficient. Attenuation due to Mie scattering is a function of the visibility and laser wavelength [13]:

$$\sigma = \beta_a = \frac{3.91}{V}\left(\frac{\lambda}{550nm}\right)^{-q} \quad \ldots\ldots 8$$

Where:

λ = wavelength in nanometers,

V = visibility in kilometers.

q = the size distribution of the scattering particles, =1.6 for high visibility (V >50 km), = 1.3 for average visibility (6 km<V<50 km), = 0.585 $V^{1/3}$ for low visibility (V<6)

The third form of scattering is *Nonselective scattering* happens where the particle size is significantly greater than the radiation wavelength. An example of this scattering kind is that at raindrops. In this case, light is mainly scattered in the forward direction. This case can be represented with geometric optics of raindrops.

Table 6. Rayleigh scattering and the aerosol attenuation coefficients at sea level with various wavelengths [14].

λ(μm)	γ (0)	σ_a (0)
0.27	2.282×10^{-1}	0.290
0.28	1.948×10^{-1}	0.270
0.30	1.446×10^{-1}	0.260
0.32	1.098×10^{-1}	0.250
0.34	8.494×10^{-2}	0.240
0.36	6.680×10^{-2}	0.240
038	5.327×10^{-2}	0.230
0.40	4.303×10^{-2}	0.200
0.45	2.644×10^{-2}	0.180
0.50	1.716×10^{-2}	0.167
0.55	1.162×10^{-2}	0.158
0.60	8.157×10^{-3}	0.150
0.65	5.893×10^{-3}	0.142
0.70	4.364×10^{-3}	0.135
0.80	2.545×10^{-3}	0.127
0.90	1.583×10^{-3}	0.120
1.06	8.458×10^{-4}	0.113
1.26	4.076×10^{-4}	0.108
1.67	1.327×10^{-4}	0.098
2.17	4.586×10^{-5}	0.085
3.50	6.830×10^{-6}	0.070
4.00	4.002×10^{-6}	0.063

3.2.3 Turbulence

Turbulence is a concept used to describe time-variation in pressure, temperature and density, inhomogeneity composition of the atmosphere. The pressure (and temperature) variations result in result in the inhomogeneity of the refraction index. The index of refraction variations cause the direction of light propagation to 'bend' in in different directions. Atmospheric turbulence has a major effect on the quality of the optical beam propagating through the atmosphere in free space optical (FSO) contact connections. Turbulence causes random fluctuations of the amplitude and phase of the received signal resulting in deep fades or surges of the signal. These fluctuations of the received optical signal significantly degrade the performance of the link, especially at a link distance (1 km) or longer, or if the communication takes place with a mobile platform. Fig.7 illustrates the influence of turbulence on propagation angle of optical beam.

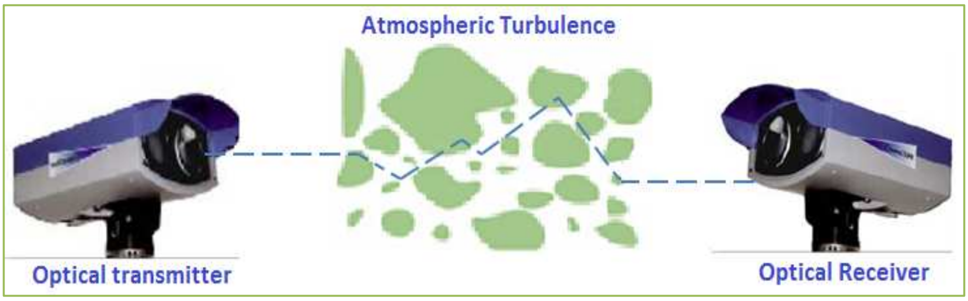

Fig.7. Influence of turbulence on propagation angle of optical beam.

The fluctuations of the refractive index in the atmosphere can be described by the index structure function:

$$D_n(r) = \langle (n_1 - n_2)^2 \rangle , \qquad \dots\dots\dots 9$$

where n_1 and n_2 are the indices of refraction at two points separated by a distance r. In a similar manner, a temperature structure function is defined by:

$$D_T(r) = \langle (T_1 - T_2) \rangle , \quad \dots\dots\dots 10$$

where T_1 and T_2 are the temperatures at two points.

The index structure parameter C_n^2 is related to the temperature structure parameter by:

$$C_n^2 = \left| \frac{\partial n(\lambda)}{\partial T} \right|^2 C_T^2 \qquad [\mathrm{m}^{-2/3}]. \ \dots\dots\dots 11$$

For dry air and optical wavelengths it can be approximated by:

$$C_n^2 \approx \left[79 \times 10^6 \frac{P}{T} \right]^2 C_T^2 \ [\mathrm{m}^{-2/3}], \ \dots\dots\dots\dots 12$$

where P is the atmospheric pressure in millibars and T is the temperature in Kelvin. For heights not near Earth' s surface (above 15 m):

$$C_n^2(h) = C_n^2(0) h^{-4/3} , \qquad \dots\dots\dots 13$$

where h is the height in meters and $C_n^2(0)$ is the ground-based index structure parameter.

In the literature, different techniques have been suggested to minimize the effects of atmospheric turbulence such as diversity, aperture averaging, adaptive optics, etc.

3.3 Optical Receiver

The optical receiver is a critical element of an FSO communications system since it often determines the overall system performance. The optical receiver's function is to detect and transform the incoming optical signal (light) into an electrical signal (voltage/current) and obtain the signal (either analog or digital) that is being transmitted from it. The optical receiver consists of a photodetector and electronics for amplifying and processing the signal. Fig.8 shows the basic block diagram of an optical receiver. The first component of the receiver is (APD) or (PIN) photodetector, which generates an electric current proportional to the level of received power. After the photodetector transforms the incoming optical signal into an electrical signal, the amplifier increases it to a level convenient for processing by the signal processor. What other circuitry is needed is determined by the modulation type and the electrical output requirements. The requirements for a photodetector are identical to those of an optical source. It should have fast response, high sensitivity, high reliability, low noise, and low cost.

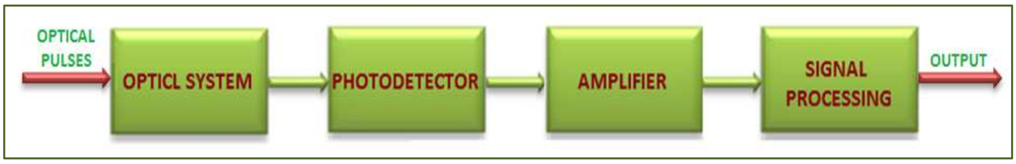

Fig.8. The basic block diagram of an optical receiver.

The photodetector component (PIN or APD) in sensors of the FSO systems plays a key role in determining system-level parameters including sensitivity, resolution, and spectral operating band. The spectral response is determined by the photodetector semiconductor material characteristics and the operating temperature. The photodetector sensitivity is a function of material (i.e., band gap), detector size, bandwidth, wavelength, and shielding. Table.7 shows most common photodetecror's material and corresponding wavelength and energy gap used in FSO [15, 16].

Table 7. Most common photodetecror's material and corresponding wavelength and energy gap used in FSO

Material	Wavelength (nm)	Energy gap (eV)
InGaAsP	1650-920	0.75-1.35
InGaAs	1700	0.73
GaAs	870	1.424
Germanium	1600	0.775
Silicon	1060	1.17

4. LOS COMMUNICATION LINK SCENARIO

When taking a closer look at how the FSO system performs, it is important that it is very important to consider the many parameters of this system. In general, these parameters can be divided into two different categories, the first being the internal parameters and the second the external parameters see Fig.9. Internal parameters are related to the design of a specific FSO system and can be impacted by the system designer or engineer. Examples include receiver sensitivity, receiver lens diameter or receiver field-of-view (FOV), transmission bandwidth, and optical power Other significant parameters that determine the performance and effectiveness of system are related to external or non-system specific parameters and all of them are related to the climate in which the system operates. Typical examples are the deployment visibility and distance.

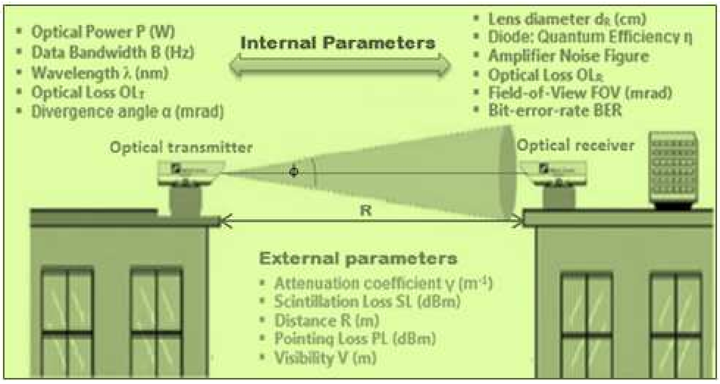

Fig.9. Schematic explanation of internal and external FSO system design parameters.

It is necessary to understand that many of these parameters are related and not independent of each other. Generally, focusing on improving one system parameter (such as increasing transmission power) does not improve the overall system performance. A professional designer of FSO system must balance all of these parameters. The simple link equation given in equation 3 illustrates the effect of various system parameters on the received power at the optical receiver. In particular, and as can be easily seen from this equation, the value of the atmospheric extinction coefficient σ is very important due to the exponential dependence on the level of the receiving energy.

$$P_R = P_T \cdot \rho \cdot \frac{d_R^2}{d_T^2 + (\phi \cdot R)^2} \cdot e^{-\sigma \cdot R} \quad \ldots\ldots 14$$

Where:

P_R = Received laser power at R,
P_T =Laser power at the source,
d_R= diameter of the receiver(m),
d_T= diameter of the transmit beam(m),
ϕ = Beam divergence (rad),
ρ = Lens-detector loss(dB),
R = Range in meters.

5. SIMULSTION, RESULTS AND DISCUSSION

According to the previous study in this work, it is advisable to choose an optical source operating within a wavelength having the lowest level of attenuation. As a result, the components of FSO systems should be designed to operate between 0.78 - 0.85 μm and 1.52 - 1.60 μm. Consequently, we have selected the following optical sources:

1. Gallium Arsenide (GaAs) LED for 850 nm atmospheric window.
2. Nd:YAG solid state lasers for 1060 nm atmospheric window.
3. $In_{(0.58)}Ga_{(0.42)}As_{(0.9)}P_{(0.1)}$ laser diode for 1550 nm atmospheric window.

5.1 Calculation of Rayleigh Scattering

Using equation 5 for Rayleigh scattering, and given data in table 6, we can conclude that in the ultraviolet and at short visible range of wavelengths Rayleigh attenuation is more important in infrared and near infrared part of spectrum. Fig.10 indicates that the Rayleigh scattering is significant up to (λ=1μm), and it becomes negligible in the infrared range of wavelengths. Consequently, in this case the specific attenuation is quiet less for 1550 nm as compared to 1060 nm, and 850 nm. As a result, 1550 nm laser are preferred choice during heavy attenuation because of their high transmitted power.

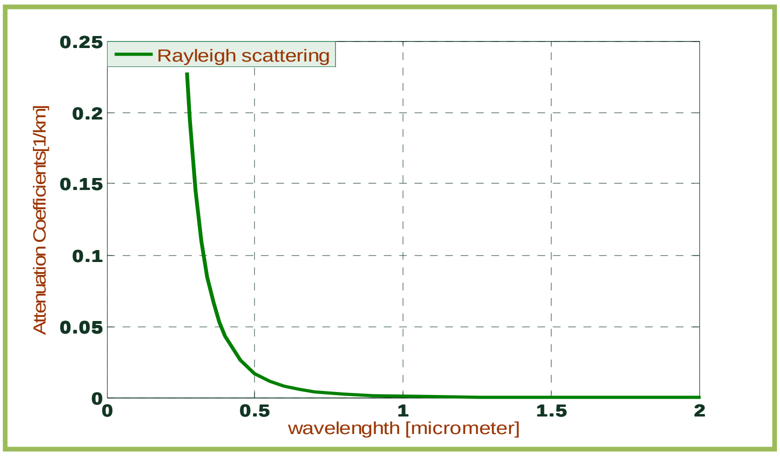

Fig.10. Rayleigh attenuation coefficient versus wavelengths.

5.2 Calculation of Mie Scattering

In contrast to Rayleigh attenuation, the Mie attenuation coefficient has more pronounced effect on the attenuation. It is significant for three wavelengths and falls rapidly with increased visibility. Using equation 8 we can calculate attenuation coefficients for 850 nm, 1060 nm, and 1550 nm wavelengths and visibility. Fig.11shows the attenuation due to Mie scattering variation of the visibility for three optical source wavelengths GaAs LED (850 nm), YdYAG laser (1060 nm), and InGaAsP LD (1550 nm). We note that when the weather is in low visibility, all three wavelengths of the optical source are packed almost closely following the same pattern which means that the specific attenuation is independent of the choice of operating wavelength.

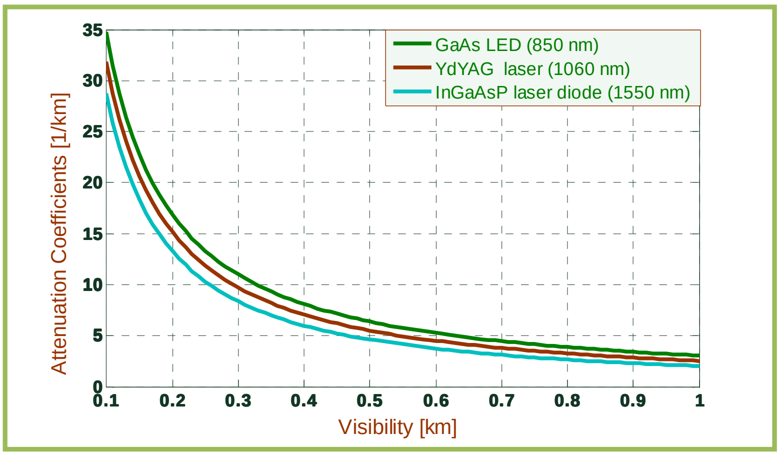

Fig.11. Attenuation coefficient due to Mie scattering as function of visibility for GaAs LED, laser, and InGaAsP LD light sources.

5.3 Calculation of Visibility

Fig.12 shows the power attenuation of GaAs LED, YdYAG laser, and InGaAsP LD respectively as it propagates from the transmitter to the receiver at a variable distance between them, whit visibility as Parameters. It can be seen that attenuation increases with range and decreases with visibility increase.

However, for a given range attenuation decays slower for higher visibilities. The calculations were done using Equation 14 according to the data given in table 8.

Table 8. Parameters Used for Numerical Calculation

Parameter	Value
Diameter of the transmit aperture (d_t)	0.05 m
Diameter of the receive aperture (d_r)	0.1 m
Beam divergence angle (φ)	0.001 (red)
Range (R)	100-1000 m
Transmission wavelength	850nm, 1060nm, 1550 nm
Lens-detector loss (ρ)	1.5 dB

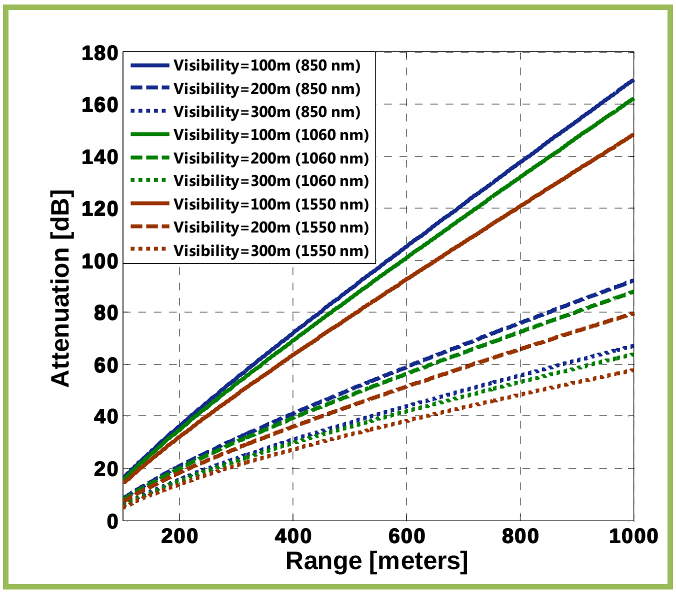

Fig.12. Attenuation of GaAs LED, YdYAG laser, and GaAsP laser diode power versus range for various visibilities.

5.4 Calculation of Divergence

Similar investigation is done for the various values of the divergence as shown in Fig.13. The divergence weakly affects the attenuation for a range of values taken into analysis. Even in this case the major parameter determining the attenuation is the visibility.

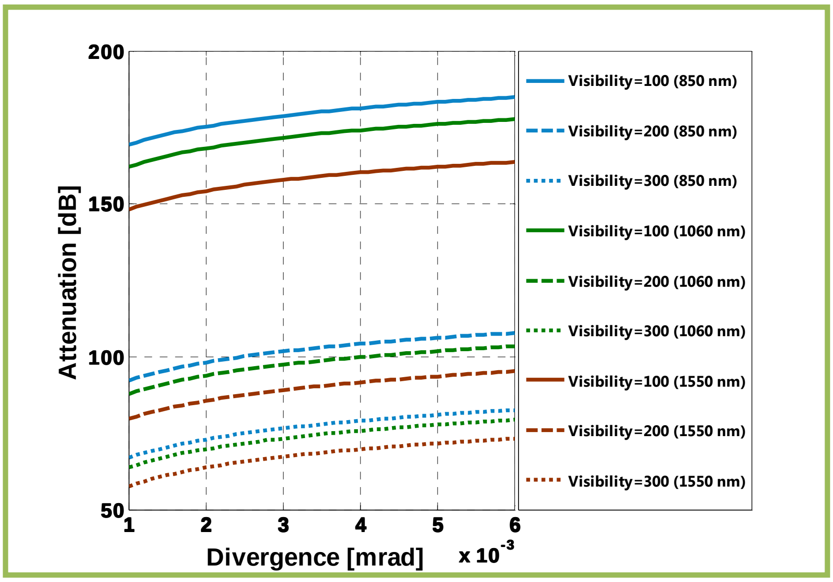

Fig.13. Power attenuation of GaAs LED, YdYAG laser, and GaAsP laser diode versus divergence, visibility and wavelengths.

5.4 Calculation of Required Optical Power

In order to provide a basis for link fabrication, it is necessary to predict required optical power of transmitter independence on the maximum allowed range between transmitter and receiver and for given sensitivity of the receiver. In our analysis we assume that the minimum detectable power for receiver is P_R=[-40dBm], corresponding to low-sensitive photo diode. The calculations were done according to the data given in Table 8. Fig.14 shows the minimum transmitter power versus link range for three different visibilities. For smaller ranges (up to 400m) the minimum optical power of transmitter increases significantly, and for larger ranges this dependence becomes linear. It can be seen that the required power of transmitter increases when visibility decreases.

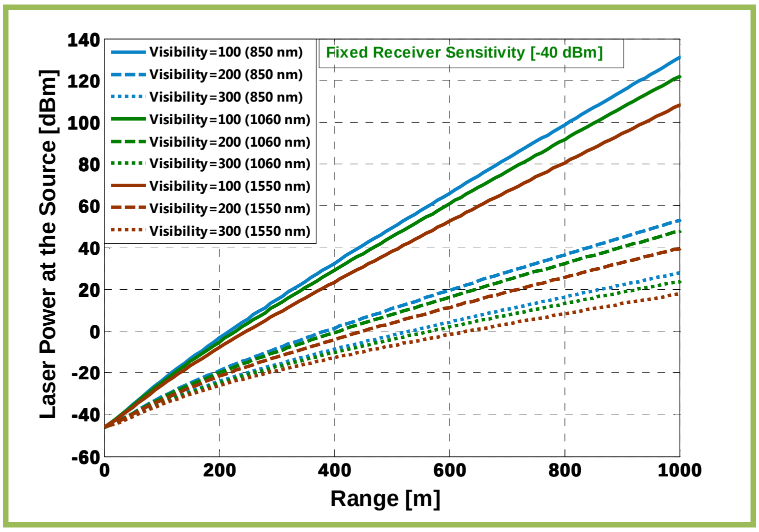

Fig.14. Required optical power of transmitter versus link range for various visibilities levels and [-40dBm] receiver sensitivity.

5. CONCLUSION

The influence of atmospheric conditions parameters including, absorption, scattering, and visibility on free space optical links has been simulated and discussed. The obtained results have been confirming the important dependence between the atmospheric attenuation, environmental conditions, and operating wavelengths of optical sources. The results also show that Rayleigh scattering can be neglected for the wavelength range of interest, while it is not the same case with the Mie scattering. In addition, it is proved that longer wavelength of InGaAsP laser diode (1550 nm) light are less attenuated in comparison with shorter wavelengths of the other two sources Nd:YAG lasers (1060 nm) and GaAs LED (850 nm), so the system efficiency is better when use of InGaAsP in bad atmospheric conditions.

The most interesting conclusion is that the range linearly depends on visibility, while increase of emitted optical power slowly increases the maximum link range.

Obviously, the attenuation increases as the divergence increases and there is no change in the attenuation due to wavelengths change.

In order for FSO systems to perform properly; the beam divergence must be adjusted to suit the receiver FOV. Where there is a relationship between the beam divergence of the transmitter and the FOV of the receiver unit. Hence, if the link head moves both the transmitted beam and the receiver's directions may be change.

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