Volume 4, Issue 8, August 2014 ISSN: 2277 128X
International Journal of Advanced Research in Computer Science and Software Engineering
Research Paper
Available online at: www.ijarcsse.com

Review Paper: Free Space Optics

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***Abstract**— Today's demand is a communication link with maximum performance and minimum errors. Free Space Optics is a medium with high bandwidth having maximum data rates and security issues favouring its promotion for the present era. Turbulent atmosphere affects the performance of the link. Humidity, water vapour, signal absorption, beam scintillation, spreading and wandering are some of the factors which causes laser beam degradation. Maintaining a free space optical link between two junctions is a tough challenge and needs enhancement in its features. This survey paper discusses the difficulties of developing free space optical links. It also tells us the basic structure of FSO, how we can improve its performance and effect of atmospheric attenuation on the signal.*

***Keywords**— Free Space Optics (FSO), Infrared Region (IR), Pseudo Random Code Generator (PRBS), Return- to –zero (RZ), Chipped Return-to-zero (CRZ), Non Return- to-zero (NRZ), Photodiiode (PD), Radio Frequency (RF), Vertical Cavity Surface emitting laser (VCSEL), Dense Waelength Division Multiplexing (DFWDM), Bit error rate (BER), Field of View (FOV), Avalenche Photodiode (APD), Gallium arsenide (GaAs), Aluminium gallium arsenide (AlGaAs), Indium gallium arsenide nitride (InGaAsN), Differential Phase Shift Keying (DPSK), Differential Quadrature Phase Shift Keying (DQPSK), On Off Keying (OOK).*

I. INTRODUCTION

FSO communication is a boon nowadays due to its advantages like high bandwidth with maximum data rates, lower cost & easier installation as compared to optical fiber system. It has many advantages such as no spectrum license requirements and immunity to interference which makes FSO very unique system for wireless communication [1, 2].

A. What is FSO?

Free- space optics (FSO) refers to the transmission of modulated visible or infrared (IR) beams through the atmosphere to obtain broadband communication. FSO is a wireless system which offers a solution to many problems. It minimizes the cost of cabling and offers simple network infrastructure. The working of FSO is very simple. FSO system consists of an optical source and a lens on the transmitter side which sends signal to the other lens on the receiver side. The transceivers have an advantage that they don't require an RF license. The type of modulation to be used depends on the distance which is to be travelled by the signal in different weather conditions. The optical transmitter has three subsystems. There is a generator for representing transmitted data. The generator is known as Pseudo Random Binary Sequence (PRBS) generator. Its output is in the form of binary pulses: a sequence of "1" (ON) and "0" (OFF). Then it has a subsystem which makes the pulses of the transmitted signal using line-coding (Return-to-zero(RZ), Chirped Return-to-zero(CRZ), Non Return-to-zero(NRZ) etc.). The third subsystem is the direct modulated lasers. In this transmission laser beams are used. So FSO is communication at the speed of light in atmosphere. This makes the technology named as free-as-air technology [17]. The stability and quality of the link is highly dependent on atmospheric factors such as rain, fog, dust and heat. Laser beam is transmitted from one lens to another for transmitting a signal. If the source doesn't produce a sufficiently parallel beam to travel the distance, collimation can be done with the lenses. Collimation means narrowing a beam of particles so that they can move in a specific direction. As a result, there is a long transmission [3].
Now at the receiver side, there is a detector known as photodiode (PD) followed by a front end amplifier and a low pass filter. The received beam is intercepted by PD, the data is detected from the transmitted beam and signal is amplified. Basically, the receiver is used to regenerate electrical signal of the original transmitted and modulated signal [4].

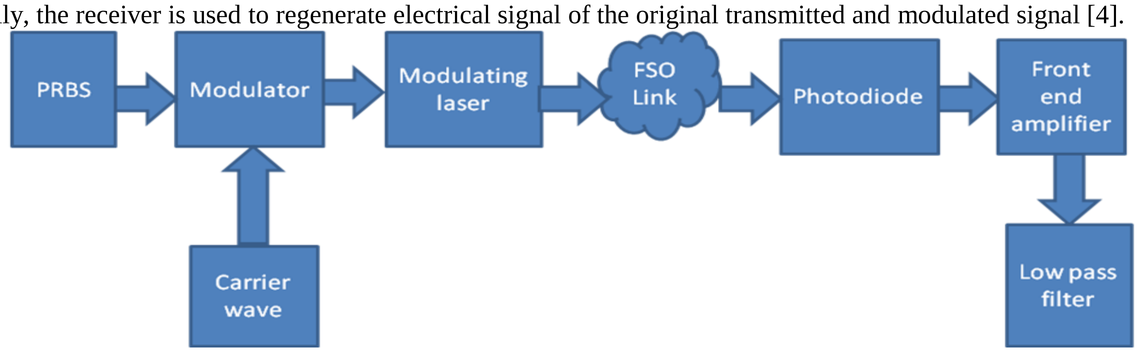

Fig. 1 Basic FSO link

While establishing a communication link between a transmitter and a receiver we have to check different conditions. Atmospheric conditions, distance between transmitter and receiver, free nodes at the transceivers, line of sight etc. are some of the parameters which are to be kept in mind at the time of setting up of a communication link. Line of sight and signal travelling distance are some of the physical issues which can limit the performance of a network. If there are some physical obstacles like buildings, trees etc. then there is a primary issue of making a line of sight for the transmission of the signal. In addition, technical issues like availability of free nodes at transceivers at the time of transmission also play a vital role in the performance of system. If there is no free node left at the transceiver and there is a continuous transmission of data, then the probability of interference of signals increases [5].

B. Why FSO?

Over the last decade, mobile networks have evidenced stupendous progress. It has the ability to stay connected on the move. Wireless networks have been dominated by IEEE 802.11 standards [6]. These networks are known as Wireless Fidelity (Wi-Fi) networks. A Wi-Fi network has two modes: infrastructure mode and the ad hoc mode.

- In infrastructure mode mobile nodes communicate through base stations whereas in ad hoc network there are wireless nodes which communicate in a peer to peer fashion in which every node serves as a host and a router at the same time. These networks are mostly used but have some disadvantages. These networks form a large number of confined hot spots. But rapid installation and cost effectiveness provide the extendibility of the network defeating the major problem of confined hot spots. FSO simplifies floor planning. These networks are a suitable solution for static as well as dynamic demand.

There are two transmission techniques for wireless communication: Radio frequency (RF) and Free Space Optics (FSO). RF wireless offers a wide range of coverage with compatible devices. The congestion and the limitations on bandwidths of the radio frequency spectrum have inhibited unrestricted growth of radio wireless systems [7]. Due to which optical wireless system is believed to be a long term option for wireless transmission.

RF systems have the ability to penetrate physical obstructions resulting in low blocking probability of the signal. If we have to operate at high frequencies then expensive components must be used. As a result, RF systems operate at low carrier frequencies which limit the data rate. But for high coverage capability, high frequencies are essential which can also improve the data rate. In addition, operations of RF systems, at some frequencies, need license. And to obtain such licenses lead to different issues. There is no doubt that RF wireless systems will be going to serve in the field of FSO but in contrary there is a development of infrared wireless systems [8].

IR systems require no license, offer unregulated spectrum and provide unlimited bandwidth. These systems are manufactured using inexpensive components which consume little power compared to RF systems. These don't interfere with relatively nearby signals therefore, they are more immune to fading than RF. These require low operating power leading to cost and energy saving. But as we know a coin has two sides, likewise, FSO signals are more hazardous to human eye. To reduce the affect of these signals, we have to lower the level of used power, due to which sensitive receivers are needed leading to increased system complexity [8]. The merits of full optical FSO communication system make it a strong candidate for accessing technology.

C. Improvement of FSO Using Optical Interconnects and Amplifiers

FSO when combined with optoelectronic devices promise large interconnection density, high distance bandwidth product, low power dissipation and superior crosstalk performance at high speeds [9]. Optoelectronic devices are electrical-to-optical and optical-to-electrical transducers. These are the electronic devices that source, detect and control light. There are some interconnects like vertical cavity surface emitting lasers (VCSELs), light modulators etc. and they can enable high speed FSO. VCSEL is a laser diode that revolutionizes fiber optics communication by improving efficiency and increasing data speed. These emit energy at 850nm and 1300nm correspond to IR portion. Materials used are Gallium arsenide (GaAs), aluminium gallium arsenide (AlGaAs), Indium gallium arsenide nitride (InGaAsN) [10]. The VCSELs operate at 850nm with 15°- divergence angle and the detector aperture is 80×80 µm. Laser drivers, receivers (amplifiers), and router circuits are integrated on silicon chips and are included in the systems. Data can be fed to electrically to any of the silicon chips and routed to the VCSELs through driver circuits and can be readout electrically from each silicon chip independently [11]. It has many advantages like it is easy to test, more efficient and have cheaper manufacturing. It has less current requirement to produce a coherent energy output. It emits a narrow circular beam which makes it easier to get the energy from the device into an optical fiber.

Generally, today's FSO systems operate in the near wavelength range between roughly 750 nm to 1600nm. Usually we use 1550nm because of its different features such as it is compatible for long distances and gives us high data rates [17].

D. Advanced DWDM FSO System

This is one of the attractive applications in FSO. In this scenario, various kinds of wireless signals can be transmitted using DWDM full optical FSO links. Using DWDM we can get a good transmission over distances. DWDM is a technology that puts data from different sources together on an optical fiber, with each signal carried at the same time on its own separate light wavelength. Using DWDM, up to 96 wavelengths or channels of data can be multiplexed into a light stream [12,14]. It is a technique for increasing the bandwidth of an optical network communication. The bandwidth is carved up into wavelength channels, each of which carries a data stream individually. There are different architectures used for implementing this technique. Different channels modulate the data at their levels and the after multiplexing gives it to the laser beam for transmission.

II. PERFORMANCE

As we have seen FSO is a channel which offers us many advantages over different channels for communication. But the performance of FSO depends upon several parameters. These parameters can be divided into many two categories: internal parameters and external parameters. Internal parameters are concerned with design of an FSO system and include optical power, wavelength, transmission bandwidth, divergence angle and optical loss on the transmitter and receiver sensitivity, bit error rate (BER), receive lens diameter, and receive field of view (FOV) on the receiver.

External parameters are related to the environment in which the system is to show its result. The parameters include visibility or line of sight, atmospheric attenuation, scintillation etc. which come under the effects caused by different atmospheric conditions.

It is important to understand all these parameters before designing a system so that a system can give its best performance. The link performance always depends on the atmospheric conditions in which the signal has to travel. Alignment of antennas, transceiver design is also some of the parameters which also affect the performance.

Link budgets give the performance of FSO. Link budgets include input power, sensitivity losses which are due to scattering, absorption, reflections and receive sensitivity, optical system losses, geometric losses and alignment loss.

- Geometric losses are those losses that occur due to the spreading of transmitted beam between transmitter and the receiver. The beam spreads to a size larger than the receive aperture and the stuffed energy is lost [13].

$$\text{Geometric Loss(dB)} = 10\times\log\left[\frac{\text{Receiver Aperture diameter(m)}}{\text{Transmitter Aperture(m)} + [\text{range(km)} \times \text{Divergence(mrad)}]}\right]^2$$

- Mispoint loss represents the imperfect alignment of the transmitter and the receiver, due to which the transmitter's and the receiver's parameters get changed. So the exact transmitted power couldn't reach the receiver and energy loss is there. A system should be perfectly aligned to avoid loss of energy. In general, a system is perfectly aligned when the centre of the Gaussian power distribution is at the centre of the receiver. If this is not the case then the receiver will only receive from the edges of the beam and as a result, the intensity of the received energy is lower than the expected one [13].

A. Performance Enhancement

System Modelling:

The system performance is highly sensitive to the atmospheric turbulence. The final goal is to set up the optical transmitter so that we can achieve the highest modulation levels or power without creating unacceptable distortions.

With time, the number of services being delivered by the operators is increasing. So it is crucial that the system gives good performance. Before setting up a network, there are many parameters for which the operator should be very careful to avoid inaccuracies to obtain good performance in the field. By initially, checking the different variable parameters like weather conditions, power, wavelength etc. and checking them in the future, operators can ensure the performance of the system [14].

Reception Diversity System:

To improve the performance of a system we use diversity scheme in which many receivers are used to receive the signal. The received optical signal is collected by multiple receiving apertures, optically combined, amplified by an optical pre-amplifier and finally detected by a photo detector.

Depending on the model, we can adjust the different param parameters like optimal values of the system parameters such as receiving aperture size, pre-amplifier gain, transmitting power etc. [15]. In this process, we use more than one antenna at the receiver side and the fading distribution of each receiver is independent. According to the atmospheric conditions, the signal travels to the receiver and the antenna receiving the signal with maximum strength i.e., giving the maximum performance is being chosen for the further proceedings.

A diversity scheme refers to a process of improving the reliability of a message by using two or more communication channels with different characteristics independent of each other.

The following classes of diversity scheme can be used:-

- Polarization Diversity: Polarization diversity combines pairs of antennas with orthogonal polarizations (i.e. horizontal/vertical, ± slant 45°, Left-hand/Right-hand etc.). Reflected signals can undergo polarization changes depending on the medium through which they are travelling. A polarisation difference of 90° will result in an attenuation factor of up to 34dB in signal strength. By pairing two complementary polarizations, this scheme can immunize a system from polarization mismatches that would otherwise cause signal fade [16].
- Time Diversity: Multiple versions of the same signal are transmitted at different time instants. A redundant forward error correction code is added and the message is spread in times by means of bit interleaving before transmission. It is used to overcome the signal from error bursts due to time varying channel conditions. The error bursts may be caused by fading in combination with the moving receiver, transmitter or obstacle or by intermittent electromagnetic interference from transmitters [16].
- Frequency Diversity: The signal is transmitted using several frequency channels or spread over a wide spectrum.
- Space Diversity: Spatial diversity employs multiple antennas, usually with the same characteristics, that are physically separated from one another. Depending upon the expected incidence of the incoming signal, sometimes a space on the order of a wavelength is sufficient [16].

Advanced tracking Mechanism

As a signal travelled in space experiences different conditions surely affecting its efficiency. The random changes in its parameters are due to change in refractive index along the transmission path. These variations produce fluctuations in both intensity and phase of an optical wave propagating through the medium, limiting the performance of the communication system.

The systems thus need specially designed terminals and accurate coupling techniques. In that case tracking subsystem is the most important key element. This subsystem is based on movable mirrors that control the direction in which the beams are launched. A feedback mechanism continuously adjusts the mirrors so that the beams stay on target [17].

A system with improved tracking scheme and optimised system design would be necessary to provide better transmission availability for wireless services. If a system provides for automatic pointing and tracking, then the beam width can be narrowed significantly (typically, 0.05-1.0 mrad of divergence, which is equal to a beam spread of 5cm to 1m at 1km) [13].

Beam Divergence

When the beam propagates outward, it slowly diverges or fans out. For an electromagnetic beam, beam divergence is the angular measure of the increase in the radius or diameter with distance from the optical aperture as the beam emerges. The focal distance of the transmitter lens is adjusted to diverge the laser beam in the FSO system. Such a way is adopted to enlarge the beam spot at the receiver, and it is expected that using this way can enhance the performance of the link [18].

III. ATMOSPHERIC ATTENUATION

The performance of an FSO link is affected by different weather conditions. The occurrence of snow, rain, drizzle, fog, haze, dust/ sand will lead to absorption and scattering of the transmitted signal.

The specific atmospheric attenuation $\gamma_{atmos} = \gamma_{clear\ sky} + \gamma_{excess}$

where $\gamma_{clear\ sky}$ is specific attenuation under clear sky and γ_{excess} is specific attenuation due to the presence of fog, mist, rain, snow etc. The atmosphere is a varying medium and as a result γ_{atmos} is a stochastic process [19].

There is an approximate relationship between wavelength and scatter's attenuation coefficient. Scattering depends upon the scatter's size r with respect to the transmission wavelength λ. Q(λ) signifies the quantity of attenuation of a propagation medium, penetrated by a beam of light travelling at certain wavelength.

Table 1 Scatter size depending on different scattering

Rayleigh scattering	Mie scattering	Non- selective or geometrical scattering
$r \ll \lambda$ $Q(\lambda) \sim \lambda^{-4}$	$r = \lambda$ $Q(\lambda) \sim \lambda^{-1.6}$ to $Q(\lambda) \sim \lambda^{0}$	$r \gg \lambda$ $Q(\lambda) \sim \lambda^{0}$
Because of Air molecules, Haze	Because of Haze, Fog, Aerosol	Because of Fog, Rain, snow, Hail

- Particles which are larger than the wavelength, scattering can be described by geometric optics which is independent of laser wavelength.
- Particles which are comparable to laser wavelength, Mie scattering theory can be applied.

A. Mie Scattering

It is related to visibility.

- The specific attenuation due to fog, $\gamma_{fog}(\lambda)$ (dB/km), which is given by the equation:

$$\gamma_{fog}(\lambda) = \frac{3.91}{V}\left(\frac{\lambda}{550\ nm}\right)^{-q} \qquad \text{...............(1)}$$

where

V= visibility (km)

λ =wavelength (nm)

q = a coefficient dependent on the size distribution of the scattering particles. It has some experimental data given by:

$$q = \begin{cases} 1.6 & V > 50km \\ 1.3 & 6km < V < 50km \\ 0.585V^{\frac{1}{3}} & V < 6km \end{cases} \qquad \text{.................(2)}$$

- The specific attenuation due to rain γ_{rain} (dB/km) is given by the relation [19]:

$$\gamma_{rain} = k.R^{\alpha} \qquad \text{.................(3)}$$

where the parameters k and α depend on the rain characteristics if determined for different places.

- The specific attenuation due to snow γ_{snow} (dB/km) is given by the relation [19]:

$$\gamma_{snow} = \alpha . S^b \qquad \text{................(4)}$$

where γ_{snow} : snow attenuation due to snow (dB/km)

S: snowfall rate (mm/h)

α and b: functions of the wavelength, λ(nm) which can be estimated for places.

B. Scintillation Losses

When a signal is transmitted over a channel then it experiences many obstructions like change in refractive index, introduction of buildings, different weather conditions and many more. Humidity, water vapour, fog, signal absorption, beam wander and beam spread are some of the difficulties which a signal faces during transmission [20]. As we are discussing about weather conditions, thermal conditions also play a major role in the performance of a network. Under the influence of thermal turbulence inside the propagation medium the propagated wave sometimes get defocused from the path leading to the loss which is known as scintillation loss [21]. The fluctuations in the signal depend on the intensity of the solar turbulence. The scintillation loss can be calculated as [20]

$$\alpha_{scin} = \sqrt{23.17\left[\frac{2\pi}{\gamma}\left[10^9\right]\right.^{\frac{7}{6}} C_n{}^2 l^{\frac{11}{6}}\Big]} \text{ (dB)} \qquad \text{............(5)}$$

where λ represents the transmitter wavelength in nm

l is the channel length in metre

$C_n{}^2$ is the refractive index structure parameter in $m^{\frac{-2}{3}}$.

- For low turbulence $C_n{}^2$ is 10^{-16}
- For moderate turbulence $C_n{}^2$ is 10^{-14}
- For high turbulence $C_n{}^2$ is 10^{-13} [22]

C. Fog Attenuation

The signal degradation due to fog is determined by some models. Several models exist which allow to calculate specific attenuation for different optical wavelengths based on visibility data. The two most widely models used and simulated in optical simulation is Kruse model and the Kim model [19]. The specific attenuation is calculated by the equation (1), with the variables visibility V(km), wavelength λ(nm), visibility reference at wavelength λ_0(nm).

$$\alpha_{spec} = \frac{10\log V}{V}\left(\frac{\lambda}{\lambda_0}\right)^{-q} \qquad \text{............(6)}$$

The wavelength dependency in this expression is expressed by q, which is in the Kruse model given by the equation (2) and in the Kim model given by equation (3) [23-25].

$$q = \begin{cases} 1.6 & V>50km \\ 1.3 & 6km<V<50km \\ 0.585V^{\frac{1}{3}} & V<6km \end{cases} \qquad \text{............(2)}$$

$$q = \begin{cases} 1.6 & V>50km \\ 1.3 & 6km<V<50km \\ 0.16V+0.34 & 1km<V<6km \\ V\text{-}0.5 & 0.5km<V<1km \\ 0 & V<0.5km \end{cases} \qquad \text{...........(3)}$$

D. Window Attenuation

As the signal passes through the atmosphere so some kind of attenuation is added to the signal. Windows allow optical signal to pass through them, they all add some kind of attenuation to the signal depending upon the material of windows. Windows that are coated or tinted can have much greater attenuation [17]. For a good performance of the signal, installer at the time of installation need to check the attenuation caused due to windows so that actual performance of the signal can be estimated. The installer also needs to check the possibility of degradation of the signal due to clouds. So the link performance can be calculated as

Link performance = Window attenuation+ Attenuation due to low clouds.

E. Allignment

This is one of the challenges for FSO system. FSO transceivers transmit directional beams of light which the receiver has to receive. For this a directional antenna is required at the receiver side. The transmission takes place depending upon the cone of acceptance which should be similar at both the ends [17].

F. Swaying Building

One of the more common difficulties that arise when deploying free space optics links on the buildings or towers is sway due to wind or seismic activity [18]. Storms and earthquakes can cause buildings to move enough to effect beam aiming. So this ultimately results in the degradation of the performance of the signal. Beam divergence and active tracking system can be used to overcome the problems caused by swaying buildings.

IV. MODULATION TECHNIQUES USED

It is a process in which the data signal is modulated with a carrier signal so that it can be transmitted over a channel. It can be done by various methods which are amplitude modulation, phase modulation and frequency modulation. Whenever a signal is transmitted over a channel it experiences fluctuations in amplitude and phase, known as scintillation which may be due to refractive index change caused by different weather conditions. It degrades the performance of an FSO communication. To deal with this, different modulation approaches have been used.

A. The Performance of OOK-NRZ and RZ Modulation Techniques

To improve the BER performance of a link due to scintillations, selection of appropriate modulation schemes is an important factor which determines the overall system performance. On-Off shift keying is the simple and widely adopted modulation scheme. In this a transmitted 1 is on and transmitted 0 is off. It has simple receiver design, bandwidth efficiency and cost effectiveness. From the view point of the receiver, RZ has been reported to offer better performance over NRZ in FSO links [21].

- RZ coding has come into fashion for long distance because it has a higher peak power, a higher S/N ratio, a lower bit error rate than NRZ encoding [22].
- RZ pulses always create distinct transitions between encoded bits (ones being 'on' and zeros being 'off') and thus create a much cleaner optical signal for the receiver to read [22].

The improved modulation techniques are DPSK, DQPSK etc. but the above discussed i.e., OOK technique is best known for its simplicity.

B. Adaptive Modulation using RF Feedback

Adaptive modulation is a term which is useful for error free long distance transmission. It is a technique which is adaptive to the conditions provided by the atmosphere. In this technique the channel conditions are estimated at the receiver side and feed this signal to the transmitter using an RF feedback channel, so that the transmitter can be adapted relative to the channel conditions. There is an RF backup channel which is used to provide communication under severe atmospheric conditions if some signal loss is there.

Adaptive modulation is a term used in wireless communication to denote the modulation of the data signal with the carrier and then after transmission used to check the weather conditions so that the modifications can be done before transmission [26].

The basic functioning of this feedback channel is that the signal is transmitted through a wireless channel and an optical system is there at the receiver. An optical system collects the incoming light and focuses it onto a detector, which generates an electrical current proportional to the intensity power. The intensity channel estimate is transmitted back to the transmitter by using an RF feedback channel. In this way the performance of a channel is improved using the RF feedback.

V. CHOICE OF WAVELENGTH

FSO system operates in the near IR wavelength range between 750 and 1600nm.

A. 780-850 nm

These wavelengths are chosen according to the requirement of the system. At 780 nm, inexpensive CD lasers are available, but the average lifespan of those lasers is an issue.

Around 850nm, reliable, inexpensive, high performance transmitter and detector components are there like Silicon avalanche Photo Diode (APD) is which VCSEL technique can be used and whose disadvantage is that the demodulation of beam is not possible with this technique [27].

B. 1500-1600 NM

These wavelengths are good for FSO, because of high quality transmitter and detector components. WDM is used in this because of which we can be able to get more data due to multiplexing but interference increases in this technique. Ultimately 50-65 times as much power can be transmitted at this frequency that can be transmitted at 780-850nm for the same eye safety [22].

Generally the equipment works at one of the wavelength 850nm or 1500nm. Lasers operating at 850nm are much less expensive so are used for applications over moderate distances.

Direct modulated lasers based on InGaAs semiconductor technology with operating wavelength around 1550nm were developed for FSO because of low attenuation characteristics [23]. The 1550nm wavelength is used because of the following factors:-

- It can boost data rate i.e., can provide high data rates for long distances even in poor propagation conditions like fog, haze etc. In that case, 1550nm can become quite attractive.
- The 800nm wavelength affects the retina but 1550nm doesn't focus onto the retina. So the lenses operate at 1550nm.
- Eye safety regulations permit ~50 times more transmitted power at 1550nm than 850nm, which improves penetration through fog.
  - Higher power can be achieved at comparable cost as the sources, in the shorter wavelength range.
- Receivers enjoy approximately 3dB better receiver sensitivity at 1550nm due to the lower energy per photon because $E=hc/\lambda$ [28].

VI. CONCLUSION

During the last few years, FSO technology has become one of the hottest topics in the telecommunication industry because it has the most promising capabilities to the last- mile bottleneck problems. Although there are several factors that degrade FSO signal performance as well. Its performance depends upon the atmospheric conditions on which the signal travels. FSO is a transmission technique which doesn't affect eyes if the operating wavelength remains 1550nm. FSO transmits data with high bit error rate through the air between transceivers mounted on rooftops or behind windows. It works over distances of several hundred metres to kilometres. It requires no spectrum fees. Modulation techniques are used for proper transmission of the signal so that an error free signal transmission is obtained. For the long term success of this technology we expect accurate performance from the system.

ACKNOWLEDGMENT

The authors are first of all thankful to almighty, and also to the Dean, Faculty of Electronics and Communication Technology, Eternal University for providing the necessary facilities for the presentation of the paper.

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