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Review on Free Space Optics

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ABSTRACT

Present era demands high bandwidth with high data rates especially for internet. For high data rates requires high speed transmission medium like optical fiber. To overcome the bottle neck of last mile communication free space optics has emerged as a better option for radio engineers. Using Infrared beams provides license free spectrum, high bandwidth with maximum data rates. In this paper different aspects for utilizing an FSO link are reviewed showing there advantages and disadvantages.

Indexing terms/Keywords

Free Space Optics (FSO), Line of Sight (LOS), Radio Frequency (RF), Radio on Free Space Optics (RoFSO), Return to Zero (RZ), Non-return to Zero (NRZ), On Off Keying (OOK), Phase shift keying (PSK), Differential Phase Shift Keying (DPSK), Low density parity check (LDPC), Orthogonal Frequency Division Multiplexing (OFDM), Forward Error Correction (FEC).

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1. INTRODUCTION

The free space optics (FSO) communication is a recent and growing technology that has found application in many areas of the short-and long-haul communications space (from intersatellite links to interbuilding links). The terrestrial FSO systems combine some advantageous capabilities of fiber optics (high data rates, no mutual interference between the FSO systems, and difficult eavesdropping on transmitted data), and radio frequency equipment (wireless connectivity, fast and easy installation, and relatively low cost) [1].

The theory of FSO is exactly the same as that of the fiber optical transmission system. The difference is that the energy beam is collimated and sent through clear air or space from the source to the destination, rather than guided through an optical fiber. An FSO system for the outdoor environment is workable over distances of several kilometers as far as it has clear line of sight (LOS) of atmosphere between the source and the destination [2]. Fig 1 shows a FSO link between two buildings which is dependent on line of sight communication.

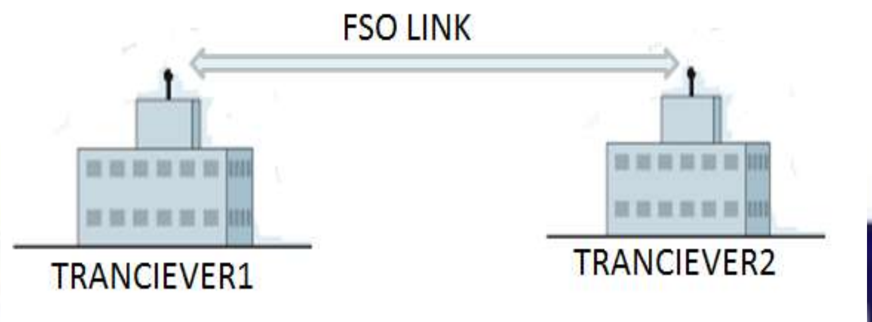

Fig 1: FSO link for outdoor connections

The optical signal provides a secure link with adequate spatial isolation from its potential interferers. The electromagnetic spectrum used in FSO is license free, its initial set-up cost is lower and the deployment time is shorter. FSO can deliver the same bandwidth as optical fiber but without the extra cost [3].

Conventionally, wireless networks were implemented as Radio Frequency (RF) systems because of the already available RF technologies. Moreover, the long experience with RF systems and the features RF presents had a great impact on the accelerated propagation of these systems. RF systems offer a wide range of coverage and have the ability to penetrate most physical obstructions resulting in high immunity to blocking. However, these "nice" features evaporate as the data rate increases because line of sight becomes essential at high frequencies limiting the coverage capability of RF systems. Furthermore, expensive components must be used to operate RF systems at high frequencies [7]. As a result, some RF based wireless systems operate at low carrier frequencies to avoid loss of the major RF advantages. Operating at low frequencies limits the data rate. Furthermore, the heavy demand on RF wireless systems has been pushing the RF spectrum to the limited. RF frequency spectrum requires licenses, obtaining such licenses is subject to technical and security issues. Contrary to RF wireless, Infrared system employed in FSO systems require no licenses, offer unregulated spectrum, and theoretically provide unlimited bandwidth. Consequently, optical technologies have the potential to be the wireless choice of the future, knowing that the congestion of the RF spectrum and the demand for broadband applications will be ever increasing. In addition to licensing and bandwidth, optical wireless has many other advantages. Infrared systems are manufactured using inexpensive components because of the simple technology needed for optoelectronic devices. These components consume little power compared to RF systems. Mobile technologies are expected to benefit the most as manufacturing optical wireless-ready mobile devices becomes simpler and inexpensive [7].

In terrestrial applications, the FSO systems are most frequently used as the last-mile telecommunications link or as the LAN link between buildings. For telecommunication (carrier-class) applications, the link availability is generally considered to be 99.999% while for the LAN applications (enterprise-class) a link availability of over 99% is usually sufficient [1-4].
FSO links can potentially be used to bridge the last mile access network gap, to provide broadband internet access to rural areas and to link mobile base station. Some of the possible applications are electronic commerce, streaming audio and video, teleconferencing, real-time medical imaging transfer, enterprise networking, work sharing and high speed interplanetary links [5].
FSO links are stout too, on March 11, 2011, a massive earthquake has struck off Japan's northeastern coast, shaking buildings in Tokyo for several minutes. At that moment, RoFSO system had to maintain the automatic data measurement. When the Mainshock reached the site, the error signal of tracking system increased significantly. Still RoFSO link was not shut down. Although there were at least three large aftershocks of magnitude 7 within one hour, high tracking error was recorded only once. Moreover, when the aftershock intensity was less than 5, the RoFSO system showed no abnormality.

Usually, after the earthquake, the main challenge that FSO communication is likely to face is the instability of the optical received power [6].

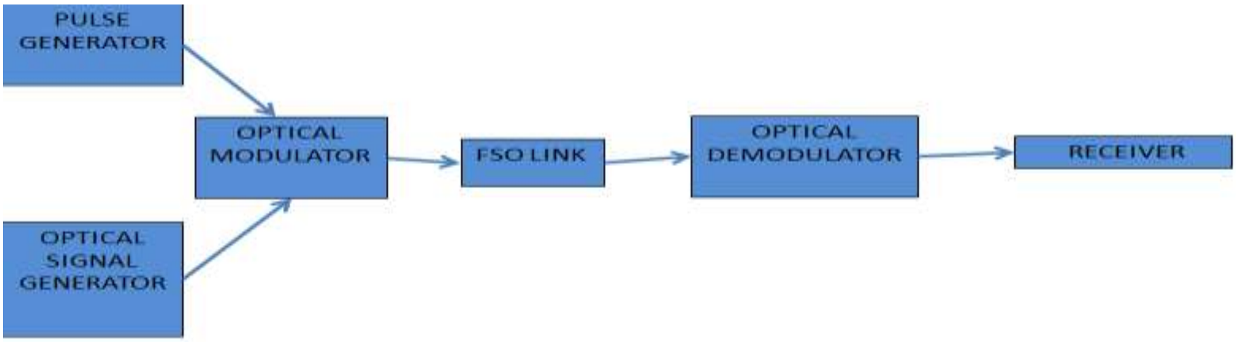

Fig 2: General schematic of FSO link.

The pulse generator generates pulses (information signal) to be transmitted through the FSO link. The pulse generators can be sine wave, triangular wave, saw up/down, Return to Zero/Non-return to Zero (RZ/NRZ) pulse, Gaussian pulse, impulse or M-ary generator. Optical carrier wave can be produced by using a LASER or LED. These pulse shape modulate the optical signal generated by laser. Further modulation of information pulse with carrier optical signal is done utilizing optical modulator. Optical modulator can be Mach-Zehnder, AM, FM or PM. Modulated signal is transmitted on FSO link then optical demodulator is used to detect electrical signal from optical signal. Demodulator to be employed can be PIN, APD, spatial PIN or spatial APD. Later demodulated signal is utilized by receiver can be in form of sound or broadband data.
The paper is organized as follows. FSO link performance with and without atmospheric attenuation is discussed in section 2. The choice of frequency for FSO link is discussed in section3. In section 4 and 5 atmospheric attenuation and scintillation affect are discussed. Section 6 covers modulation schemes in FSO and section 7 tells about hybrid FSO links.

2. FSO LINK PERFORMANCE

FSO link may or may not be affected by attenuation. Link performance thus varies according to its variety (link without attenuation or with attenuation). Both are considered in this paper.

2.1 Link without atmospheric attenuation

There can be optical links unaffected by the atmosphere. 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 [8]. The signal power received PRx [W] depends on the transmit power PTx [W], transmit antenna gain GTx, receive antenna gain GRx, the range loss Gr, and system-dependent losses Asystem,lin.

$$PRx = PTx \times GTx \times Gr \times A_{system,\,lin} \quad \text{......(1)}$$

Assuming a Gaussian beam underfilling the transmit aperture, the transmit antenna gain GTx is

$$GTx = \frac{32}{\theta^2} \quad \text{......(2)}$$

where Θ [rad] is the full-angle e^2 divergence of the transmit beam.

The range loss Gr depends on the link propagation distance L and is given by:

$$Gr = \left(\frac{\lambda}{4\prod L}\right)^2 \quad \text{......(3)}$$

Further, the receive antenna gain, with telescope aperture diameter (antenna size) D, is given by

$$GRx = \left(\frac{\prod D}{\lambda}\right)^2 \quad \text{......(4)}$$

The Asystem,lin reflects all the other system-dependent losses. It includes losses due to link misalignment, telescope losses, losses due to splitting out light for tracking systems, etc.

2.2 Link with atmospheric attenuation

The overall system performance of a link is quantified using a link margin derived from the link equation. The optical link equation is analogous to the link equation for any radio frequency (RF) communication link. Starting with the transmit power the designer identifies all link degradations and gains to determine the received signal level. The received signal level is then compared with the sensitivity of the receiver, thus giving the link margin [8].

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The link margin, *Mlink* (dB), which is the power available above the sensitivity of the receiver, can be found from equation (1):

$$M_{link} = P_e - S_r - A_{geo} - A_{atmo} - A_{scinitillation} - A_{system} \quad \ldots(5)$$

where:

Pe (dBm): total power of the emitter
Sr (dBm): sensitivity of the receiver which also depends on the bandwidth (Data rate)
Ageo (dB): link geometrical attenuation due to transmit beam spreading with increasing range
Aatmo (dB): atmospheric attenuation due to absorption and scattering
Ascintillation (dB): attenuation due to atmospheric turbulence
Asystem (dB): represents all other system dependent losses including misalignment of the beam direction, receiver optical losses, loss due to beam wander, reduction in sensitivity due to ambient light (solar radiation), etc.

3. CHOICE OF FREQUENCY

Choice of frequency is an important factor to be considered for utilizing an FSO link. Two ranges are sepecified 780-850nm and 1520-1600nm. Each range is having its advantages and disadvantages.

780–850 nm These wavelengths are suitable for FSO operation, and several vendors provide higher-power laser sources that operate in this region. At 780 nm, inexpensive CD lasers are available, but the average lifespan of these lasers can be an issue and must be addressed during system design (e.g., running the lasers at a fraction of their maximum rated output power, which will greatly increase their life). Around 850 nm, reliable, inexpensive, high-performance transmitter and detector components are readily available and commonly used in network and transmission equipment. Highly sensitive silicon (Si) avalanche photodiode (APD) detector technology and advanced vertical-cavity surface-emitting laser (VCSEL) technology can be used for operation in this wavelength. Possible disadvantages include beam detection through the use of a night-vision scope, although it is still not possible to demodulate the beam with this technique [9].

1520–1600 nm. These wavelengths are well suited for free-space transmission, and high quality transmitter and detector components are readily available. The combination of low attenuation and high component availability in this wavelength makes the development of wavelength-division multiplexing (WDM) FSO systems feasible. However, components are generally more expensive, and detectors are typically less sensitive and have a smaller receive surface area when compared with Si APD detectors that operate in the 850-nm wavelength. That being said, these wavelengths are also used in long-haul fiber systems, and many companies are working to reduce the cost and increase the performance of 1520–1600-nm components. In addition, these wavelengths are compatible with erbium-doped fiber amplifier (EDFA) technology, which is important for high-power (>500 mW) and high-data rate (>2.5 Gbit/s) systems. Finally, 50–65 times as much power can be transmitted at 1520–1600 nm than can be transmitted at 780–850 nm for the same eye safety classification, owing to the low transmission of the human eye at these wavelengths [9].

4. ATMOSPHERIC ATTENUATION

Atmospheric attenuation is having a great impact on the link margin of FSO link. The specific atmospheric attenuation Att_{atm} (dB/km) can be written as the sum of two terms:

$$Att_{atm} = Att_{clearair} + Att_{excess} \quad \ldots(6)$$

where:
$Att_{clear\ air}$: specific attenuation under clear air (due to the presence of gaseous molecules)
Att_{excess}: specific attenuation due to the occasional presence of fog, mist, haze, drizzle, rain, snow, hail, etc.

4.1 Clear-air attenuation

Attenuation under clear-air conditions is mainly the attenuation due to the absorption by gaseous molecules. Atmospheric absorption at specific optical wavelengths results from the interaction between photons and atoms or molecules (N2, O2, H2, H2O, CO2, O2, etc,) which leads to the absorption of the incident photon and an elevation of the temperature. The absorption coefficient depends on:
– the type of gas molecules; and
– their concentration.

4.2 Excess attenuation

Excess attenuation is the attenuation caused by the occasional presence of fog, mist, haze, drizzle, rain and snow particles. The presence of these particles causes an angular redistribution of the incident flux, known as scattering, and reduces the flux propagation in the original direction [11].

Scattering regimes depending on the scatter's size *r* with respect to the transmission laser wavelength as shown in table no. 1. Also shows the approximate relationship between wavelength and scatter's attenuation coefficient *Q*(λ).

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Table No. 1 Scatter size and wavelngth

Rayleigh scattering	**Mie scattering**	**Non-selective or geometrical scattering**
r<<<λ Q(λ)~ λ^{-4}	r = λ Q(λ)~ $\lambda^{-1.6}$ to Q(λ)~ λ^{0}	r>> λ Q(λ)~ λ^{0}
Because of Air molecules, Haze	Because of Haze, Fog, Aerosol	Because of Fog, Rain, Snow, Hail

4.3 Fog attenuation

Attenuation of the optical signal at a distance R, due to fog and haze, is determined by the Beer–Lambert law;

$$Att_{fog} = e^{-a(fog)}R \qquad \text{(7)}$$

where a(fog) (in per km) is the attenuation coefficient, which is given by

$$\alpha(fog) = \frac{3.912}{V(km)}\left(\frac{\lambda}{\lambda_0}\right)^{-q} \qquad \text{(8)}$$

where V is the visibility, λ is the wavelength of the transmitted signal, λ_0 is the visibility wavelength reference(550nm), and q is the size distribution coefficient of scattering.
Size distribution coefficient of scattering q can be found utilizing the models Kim or Kruse. According to Kruse model q is given as,

$$q = \begin{cases} 1.6 & if\ V > 50km; \\ 1.3 & if\ 6km < V < 50km; \\ 0.585V^{\frac{1}{3}} & if\ V < 6km. \end{cases} \qquad \text{(9)}$$

According to Kim model q is given as,

$$q = \begin{cases} 1.6\ if\ V > 50\ km; \\ 1.3\ if\ 6\ km < V < 50\ km; \\ 0.16V + 1.34\ if\ 1\ km < V < 1km; \\ V - 0.5\ if\ 0.5\ km < V < 1\ km; \\ 0 \end{cases} \qquad \text{(10)}$$

Kruse model states less attenuation for higher wavelengths but Kim model rejects this statement.
For prediction of fog attenuation one another model has also been specified called as Al-Naboulsi model. Al-Naboulsi characterizes advection and radiation fog separately and proposed two different models for advection and radiation fog. The advection fog is formed by the movements of wet and warm air masses above the colder maritime surfaces while Radiation fog is related to the ground cooling by radiations over continental surfaces. According to Al-Naboulsi the advection fog model is,

$$\alpha_{ADV}(\lambda) = \frac{0.11478\lambda + 3.837}{V} \qquad \text{(11)}$$

and radiation fog model is,

$$\alpha_{RAD}(\lambda) = \frac{0.18126\lambda^2 + 0.13709\lambda + 3.7502}{V} \qquad \text{(12)}$$

Specific attenuation for both types of fog can be calculated as [12]

$$A_{Fog}(dB/km) = \frac{10}{\ln(10)}\left(\alpha(\lambda)\right) \qquad \text{(13)}$$

For attenuation because of atmosphere different models have been purposed. But it is not specified which one describes attenuation at its best [10].

4.4 Rain attenuation

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Specific rain attenuation γ_{rain} (dB/km) is given by the relation [11]:

$$\gamma_{rain} = k.R^{\alpha} \quad (14)$$

where R represents rainfall rate(mm/hr) and k, α can be taken according to ITU recommendations as given in table no. 2

Table No.2 Values of k and α

Location	k	α
Japan	1.580	0.63
France	1.076	0.67

4.5 Snow attenuation

Snow attenuation γ_{snow}(dB/km) as a function of snowfall rate is given by the following relation [11]:

$$\gamma_{snow} = \alpha.S^{b} \quad (15)$$

where S represents snowfall rate(mm/hr) and α, b (functions of the wavelength in λ (nm)) can be taken according to ITU recommendations as given in table no. 3

Table No. 3 Values of constants α and b

Snow Type	α	b
Wet Snow	0.000102λ + 3.79	0.72
Dry Snow	0.0000542λ + 5.50	1.38

5. SCINTILLATION EFFECT

Atmospheric scintillation can be defined as the changing of light intensities in time and space at the plane of a receiver that is detecting a signal from a transmitter located at a distance. The received signal at the detector fluctuates as a result of the thermally induced changes in the index of refraction of the air along the transmit path. These index changes cause the atmosphere to act like a series of small lenses that deflect portions of the light beam into and out of the transmit path. The time scale of these fluctuations is of the order of milliseconds, approximately equal to the time that it takes a volume of air the size of the beam to move across the path, and therefore is related to the wind speed [9]. Laser beam deformation is caused by the changes in the refraction index of medium (free space or air). It is mainly due to scintillation which affects the laser beam propagation and ultimately causes fluctuation at the receiver end signal. It occurs because of atmospheric turbulence that produces many temporary areas that we call pockets or Fresnel zone. Atmospheric turbulence (such as wind) produces temporary pockets of air with different temperatures, different densities, and hence will produce different refractive index [17].

A complete evaluation of the total link loss requires an estimate of the average loss due to scintillation. In [13] measurement of scintillation on a four-beam FSO system with 20 cm receiving aperture is given operated at 1550 nm. During summer day, scintillation losses of 2.5 dB at 450 m range, and 10.5 dB at 5km range were measured. In [14] measurement of scintillation with a one-beam system, 20 cm receiving aperture is given operating at 1550 nm. Scintillation loss of 17 dB was measured at 4 km range, suggesting the adoption of a 20 dB safety power margin.
It has been shown scintillation loss increases with the operating wavelength [15]. The experimental results reported above indicate that the scintillation loss can be reduced with the use of multiple-beam systems and/or large receiving apertures. The results also indicate that the effect of scintillation is more severe in the afternoon and in the summer [16].

6. MODULATION

Overall performance of FSO link is also dependent on the modulations scheme adopted [3]. On–Off keying OOK is the simple and widely adopted modulation scheme used in commercial FSO communication system because of ease in implementation, simple receiver design, bandwidth efficiency and cost effectiveness [18].
In case of Line of Sight (LOS) and for diffuse systems in which shadowing effect matters, Multiple Subcarrier Modulation (MSM) technique performs better on diffuse systems in respect of power efficiency and fraction of channels experiencing an outage. Although LOS unshadowed links provide the best overall performance, LOS shadowed links are severely degraded. The power efficiency gap between diffuse shadowed links and diffuse unshadowed links is smaller. Disadvantage of utilizing MSM technique is less power efficient than single carrier modulation technique [19].
In [20] error probability expression over atmospheric channels is calculated under the assumption of log-normal distributed scintillation, and then the performance of Differential Phase Shift Keying (DPSK) system is compared with OOK system under the same channel conditions. Theory analysis and numerical results illustrated utilizing same bandwidth, DPSK system has a higher sensitivity than OOK, and upto certain extent DPSK format can reduce the impairment from

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turbulence induced scintillation for its threshold being signal intensity insensitive, and hence, DPSK format is very suitable for atmosphere channels and has a broad prospect in wireless optical communications.
Further OOK, PSK and DPSK are compared using 650nm Laser with scintillation rate 0.1, data rate 40GB/s which shows DPSK has good performance and the Bit Error Rate (BER) remains less than 0.1 for scintillation indices from 0.1 to 0.7.
In [21] it has been observed that external modulation gives better performance in comparison to direct modulation because direct NRZ spectrum has a strong carrier component compared to external modulated NRZ and there are dip null at multiples of the bit rate. Further, external modulation with different modulation format (NRZ, CSRZ, CRZ and RZ) has been observed that results that there is significant decrease in Q value which lies within (27–11), (26–10.5), (25.5–10.5) and (22.5–10) for transmission distance 8 km, 7.5 km, 7 km and 6 km in case of RZ, CRZ, CSRZ and NRZ modulation format respectively and in the BER case, it is observed that there is increase in BER which lies within (10^{-98} to 10^{-4}), (10^{-98} to 10^{-3}), (10^{-98} to 10^{-4}) and (10^{-42} to 10^{-3}) for transmission distance of 8 km, 7.5 km, 7 km and 6 km in case of RZ, CRZ, CSRZ and NRZ modulation format respectively.
To cover-up attenuation and scintillation problems the coding scheme should be chosen wisely. Different coding schemes can be employed like coded orthogonal frequency division multiplexing (OFDM) [22], coded multi-input multi-output (MIMO) [23], Rate less coding [24] or Low density parity check (LDPC) code [25].
In [26] simulation of worst channel condition is given when M- Pulse Position Modulation (PPM) is used withM=16 utilizing LDPC code rate 2/3 and best channel condition is when M- Pulse Amplitude Modulation (PAM) is used with M=8 utilizing LDPC code rate 2/3.This adaption enables the FSO link to transmit signal even during heavy fades upto 15 dB with encoded PPM and can increase the throughput in good channel condition with PAM signal.
In [27] it has been shown LDPC-coded orbital angular momentum (OAM) modulation scheme is capable of operating over the strong atmospheric turbulence regime and achieving 100 Gb/s optical transmission using 10 Gb/s technology allowing 10 bits/symbol transmission and represents an energy efficient scheme. The proposed coded OAM modulation based FSO communication system can be used to enable ultra-high-speed transmission to end-users, allow interoperability of various RF and optical technologies, reduce installation costs, reduce deployment time, and improve the energy efficiency of FSO communication links. The non-binary LDPC-coded OAM modulation outperforms the corresponding binary counterpart in terms of BER performance, and reduces decoder complexity as well as overall decoding latency.
From reference [28] it is clear employing noncentral chi-square distribution with 2*L* degrees of freedom spectral efficiencies below 1 bit/s/Hz, 2-PAM and 2-DPSK becomes attractive techniques. Between 1 and 2 bits/s/Hz, 4-DPSK and 4-PSK (Phase Shift Keying) are interesting options. At spectral efficiencies above 2 bits/s/Hz, 8-PSK and 16-QAM (Quadrature Amplitude Modulation) becomes the most considerable modulations. It has been shown that high-order *M*-ary QAM is not just spectrally efficient, but also can significantly improve photon efficiency in atmospheric fading as compared to high-order PSK modulation.
[3] tells in small turbulence condition comparing OOK NRZ, OOK RZ and BPSK, OOK-RZ outperforms OOK-NRZ. Comparing OOK and BPSK, BPSK performance is much better to OOK, reason being turbulence affects more on the intensity of signal than phase.
For FSO links normally used technique is OOK but with adaptive threshold to perform optimally in turbulence effect. But Subcarrier Intensity Modulation (SIM) performs much better with adaptive threshold [29].
Bit Error Rate (BER) [30] for a channel whose state information is completely known by the receiver is given by:
BER = 0.5 exp(-0.5SNR$_e$) ……………………………………………………………………………………………….(16)
where SNR$_e$ is electrical signal to noise ratio.
Results in [30] tells with for PIN photodetectors, a theoretical gain of about 38 dB in received power is attainable at a BER of 10^{-6}. Thus spatial diversity is better technique for mitigating scintillation.

7. HYBRID FSO

FSO is definitely a good solution for last mile problem but in conditions when atmospheric turbulence is extreme like in heavy fog giving 200 dB/km attenuation, communication cannot be fully dependent on FSO link. One has to go for another solution which is RF communication. The link combining FSO and RF link is named as Hybrid Link.
RF link acts as back up link to supplement the prime FSO link ensuring high overall link availability and reliability. The availability of a hybrid link comprising FSO as main link and 40 GHz backup link was measured to be 99.92% compared to 96.8% availability of FSO alone [12-31].
Under heavy fog conditions, the RF system can be used as a complementary link to achieve approximately six-fold extension in the link range for an SNR of 20 dB. Hybrid FSO/RF system minimizes performance degradation due to adverse weather effects experienced by conventional FSO systems. Nevertheless, some aspects of the hybrid RF/FSO system are to be studied, which includes system architecture design, forward error correction (FEC), diversity techniques, modulation format and signalling schemes, and signal processing [32].
Reference [12] depicts higher frequencies lead to higher attenuation and at 200 GHz specific attenuation reaching 200 dB/km is possible. Thus lower operating frequencies are preferable to be employed to achieve higher availability at low backup data rates. A combination of FSO and 40 GHz RF link promises better results under foggy atmosphere.

8. CONCLUSION

In today's emerging data networks with wireless technology FSO gives last mile solution to high speed networks. This technology is license free, initial set-up cost is lower and the deployment time is shorter with no mutual interference. On

FSO link there may or may not be atmospheric attenuation. For FSO link without atmospheric attenuation the link depends on transmitted power, received power and antenna gains. Loses in this link can be because of link misalignment, telescope losses, losses due to splitting out light for tracking systems. For link with atmospheric attenuation because of fog, haze snow or rain attenuation is dependent on particle size, giving different scattering and different models have been proposed for the scattering coffecients like Kim and Kruse. Choice of frequency is an important issue for deploying FSO link, 850nm or 1550nm range can be utilized or data rates of Gbps. Scintillation effect is an important issue for FSO link which can be overcome employing aperture averaging. OOK modulation is utilized in FSO links but experimental results shows PSK, BPSK, DPSK or QAM modulation can also be used utilizing different coding schemes. In case of extreme weather conditions Hybrid FSO link gives connectivity with low data rates.

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