The Role and Challenges of Free-space Optical Systems

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Abstract: Complementing wireless radio networks with free-space optics (FSO) achieves high data rates by modulating radio subcarriers over an optical carrier without expensive optical fiber cabling, enabling a pervasive platform for reaching underserved areas. In this paper, we review the main features of FSO for terrestrial and inter-satellite communications. Simulations of 1 Gbps data transmission through FSO links in both terrestrial and inter-satellite communications have been investigated to highlight potential atmospheric challenges in FSO.

Keywords: free-space optics (FSO), inter-satellite communication, atmospheric turbulences, radio-over-free-space optics (Ro-FSO)

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1 Introduction

Mobile radio networks have made tremendous strides in the last decade alongside the demand for more bandwidth in an increasingly information-driven economy. The total number of mobile subscribers in 2013 reported by the International Telecommunications Union (ITU) is 7.5 billion [1]. The rapid increase in traffic has incurred a substantial strain on mobile radio networks. This entails allocation of limited and expensive radio frequency (RF) spectrum to operators a progressive challenge for the ITU due to the explosive growth of the subscribers annually. Exorbitant RF licensing has driven cellular network operators to accommodate more users by reducing the cell size and to operate in microwave/millimeter frequency band so that the spectral congestion is avoided in lower frequency bands. This requires a large number of base stations to support the service area which increases the cost and system complexity. To reduce the system cost of mobile network, radio over fiber (RoF) technology may be deployed by interconnecting several base stations to a central station using an optical fiber. RoF involves modulating radio frequency (RF) subcarriers onto an optical carrier for transmission over an optical fiber network. Optical fibers are valuable in RoF systems for achieving high bandwidth and low signal loss, in addition to immunity to electromagnetic interference [2]. RoF requires the use of sharing of expensive equipment responsible for coding–decoding, multiplexing-demultiplexing, frequency up-down conversion from the centralized station to all the base stations [3]. This results in reduction in cost and system complexity.

Nevertheless, optical fibers between various base stations may not be readily installed for deployment of RoF and recabling may be complex. Furthermore, new fiber installations may increase RoF deployment cost and delay network rollout. FSO has become attractive to researchers as it provides the valuable features that are vital to transfer traffic to the fortitude of optical fiber [4]. In addition, FSO provides secure transmission because of negligible interception by using point-to-point laser signals in conjunction with lower errors than that of optical fiber transmission. High capacity, low power consumption, light weight, small sizes and low price for inter-satellite applications are other merits of FSO implementations [5–6]. The integration of FSO and radio technology provides assuring solutions as it incorporates the high data rates of optical signals, allows more flexibility in deployment, avoids high upfront costs and saves on the deployment time [7–11].

FSO may be broadly classified into FSO for terrestrial communication and FSO for inter-satellite communication as shown in Fig. 1. This paper reviews the main features of FSO for terrestrial communications as well as inter-satellite communications. FSO simulations for transmission of 1 Gbps data through an FSO link are delineated as an attempt to illustrate possible signal degradations in an FSO link. The rest of the paper is organized as follows: Section 2 describes FSO for terrestrial communications

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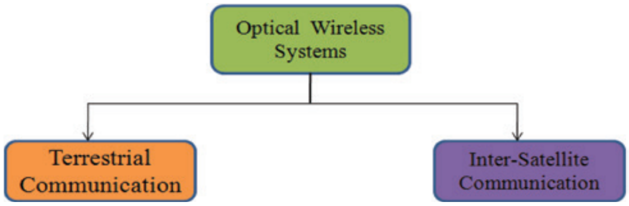

Fig. 1: Classification of optical wireless transmission

whilst Section 3 describes FSO for inter-satellite communications. Section 4 describes Ro-FSO systems and the need for a more ubiquitous wireless system. The main points are concluded in Section 5.

2 FSO for terrestrial communication

The idea of wireless optical communication originated in early 800 BC, as the ancient Greeks used fire beacons for the transfer of information from one place to another. In 1880, Alexander Graham Bell [12] invented 'photophone' which uses sunlight to transmit voice signals through an unguided atmospheric channel over a distance of 200 meters. In the early 1960's, the invention of lasers revolutionized optical communication. In 1962, researcher at Massachusetts Institute of Technology labs exhibited the remarkable transmission of television signals by employing gallium arsenide light emitting diode (GaAs LED) over the distance of 48 km [13]. In 1970, Nippon Electric Company (NEC) of Japan demonstrated the first full duplex FSO link by using 632.8 nm He-Ne laser to compensate the traffic data up to a length of 14 km between the Yokohama and Tamagawa [13]. Several experiments from the last decade further stimulated researchers in the field of FSO [14–21]. The link equation for FSO is given by the following equation [22]:

$$P_{Recieved} = P_{Transmitted} \frac{d_R^2}{(d_T + \theta R)^2} 10^{-\alpha R/10} \quad (1)$$

where d_R defines receiver aperture diameter, d_T defines aperture diameter of the transmitter, θ defines the beam divergence, R defines the range of link and α defines the atmospheric attenuation.

Today FSO is commercially available in the market, supporting data rates up to 1.25 Gbps and are designed to work in almost all reliable atmospheric conditions over the link of 3.5 km. Efforts are continuously increasing in order to boost the capacity of FSO systems by using wavelength division multiplexing (WDM) and integrated fiber/FSO transmission systems [23]. Orthogonal frequency division multiplexing (OFDM) is a mature technology for combating multipath fading in FSO. Hence, by adopting OFDM in FSO, long haul transmissions with higher data rate may be achieved [24–28]. Mode division multiplexing is a more recent development in FSO systems [29–32]. In an experiment, transmission of 4 × 42.8 Gbps is reported by employing MDM scheme over FSO [33]. In another experiment, 3 × 100 Mbps data is transmitted over FSO link by MDM [34].

FSO fulfills the quality requirements of broadband networks but there are some limitations that degrade its performance. The most dominant factor is atmospheric conditions such as fog, dust, snow or rain, resulting in scattering, absorption and deviations that debilitate the transmission paths. In an experiment, an investigation of modulation format is done by transmitting 10 Gbps of data through an FSO link [35]. The attenuations significantly influence the transmission of signal through the atmosphere and are described as follows:

(a) Fog attenuation: The atmospheric fog attenuation is persisted by the Beer–Lambert law which states that the attenuation due to fog and haze in the optical signal at a distance R is given by the following relation:

$$A_{fog} = \frac{3.912}{V(km)} \left(\frac{\lambda}{\lambda o}\right)^{-q} \quad (2)$$

where v defines the visibility in km, λ defines the wavelength of transmitting signals, λo defines the visibility reference at wavelength at λo in nm and q defines the size distribution coefficient of scattering. Kim and Kruze [36] propose the different model for the calculation of value q which is stated in Table 1.

(b) Rain attenuation: Rain is also an important parameter to be considered while designing an FSO link. The equation [37] for specific rain attenuation is described by the following relation:

$$\alpha_{rair} = 1.076 R^{0.67} \quad (3)$$

where R defines the rate of rainfall in mm/hr.

Table 1: Kim and Kruse models

Kim model	Kruze model
1.6 if $V > 50$ km	1.6 if $V > 50$ km
1.3 if 6 km $< V <$ km	1.3 if 6 km $< V <$ km
$0.16V + 0.34$ if 1 km $< V <$ 1 km	$0.585\, V^{1/3}$ if $V < 0.5$ km
$V - 0.5$ if 0.5 km $< V <$ 1 km	

Table 2: Values of b and α

Type of snow	b	α
Dry snow	$0.000102\lambda + 5.50$	1.38
Wet snow	$0.0000542\lambda + 3.79$	0.72

(c) Snow attenuation: The equation for the snow attenuation is given by the following relation [38]:

$$\lambda_{\text{snow}} = \alpha.S^{b} \quad (4)$$

where S describes the rate of snowfall in mm/hr and α & b are given according to ITU recommendations as shown in Table 2.

(d) Scintillation effect: Scintillations are also a dominant factor in FSO both in terrestrial communication as well as space communication as the optical signal is fluctuated by the transient dips caused due to change in refractive index of the medium. Atmospheric scintillation is given by the following equation:

$$A_{\text{scintt}} = 2 * \sqrt{23.17\left(\frac{2\pi}{\delta}10^{6}\right)^{7/6} * c_n^2 * l_6^{11}} \quad (5)$$

where δ is the wavelength in nm, l is the range in meter and c_n^2 is the refractive index parameter.

In this work, we have transmitted a 1 Gbps data by using a NRZ modulation technique through an FSO link for ground applications as well as inter-satellite applications which is modeled by OptiSystem™ software as shown in the Fig. 2.

The value of c_n^2 is stated as 10^{-16} for low turbulences, 10^{-14} for moderate turbulences and 10^{-12} for high turbulences [39]. Fig. 3 depicts the SNR and received power under the atmospheric turbulences. It is clearly evident from Fig. 3(a) and (b) that under clear weather conditions, the FSO link will prolong to 800 m with acceptable SNR and received power, but when the atmospheric attenuations changes due to fog, rain, snow etc, the connectivity of an FSO link is decreased. For the fog condition, the FSO link will prolong to 500 m whereas for the rain condition, the FSO link prolongs to 350 m. The link connectivity of FSO for snow is reported as 250 m with acceptable SNR and received power. The scintillation effect is also measured in Fig. 3(c) and (d), which indicates that a 14 dB in SNR degrades when the scintillations vary from low to high. Also the FSO link prolongs to 600 m under the effect of low scintillation as compared to high scintillation for which the FSO link will prolong to only 350 m with acceptable SNR and received power.

3 FSO for inter-satellite communication

In addition to terrestrial communication, FSO also has a significant role in space applications. In 1977, European Space Agency (ESA) started the program semiconductor laser Inter-satellite link experiment (SILEX) to realize the communication between satellites in space [40]. This program, which came to actual operations in 2003, led to result in making the ESA globally recognized in space inter satellite communication links. The basic application of FSO as inter-satellite is shown in the Fig. 4. SILEX is based on a combination of two optical communication payloads i.e. French Earth observation spacecraft. SPOT-4 and Advanced Relay and Technology Mission Satellite (ARTEMIS) which allows the data transmission of 50 Mbps by using GaAlAs laser diodes [40].

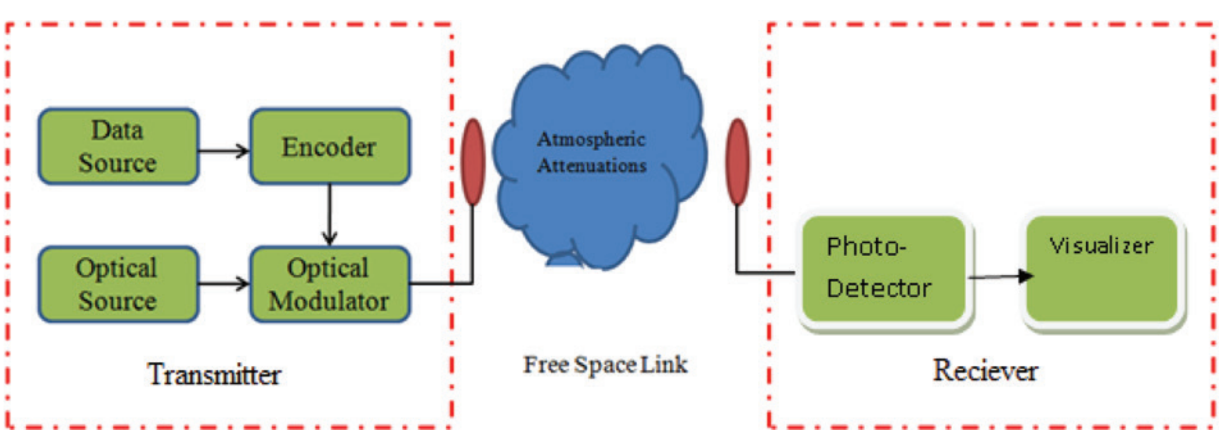

Fig. 2: Implementation of FSO system as terrestrial application

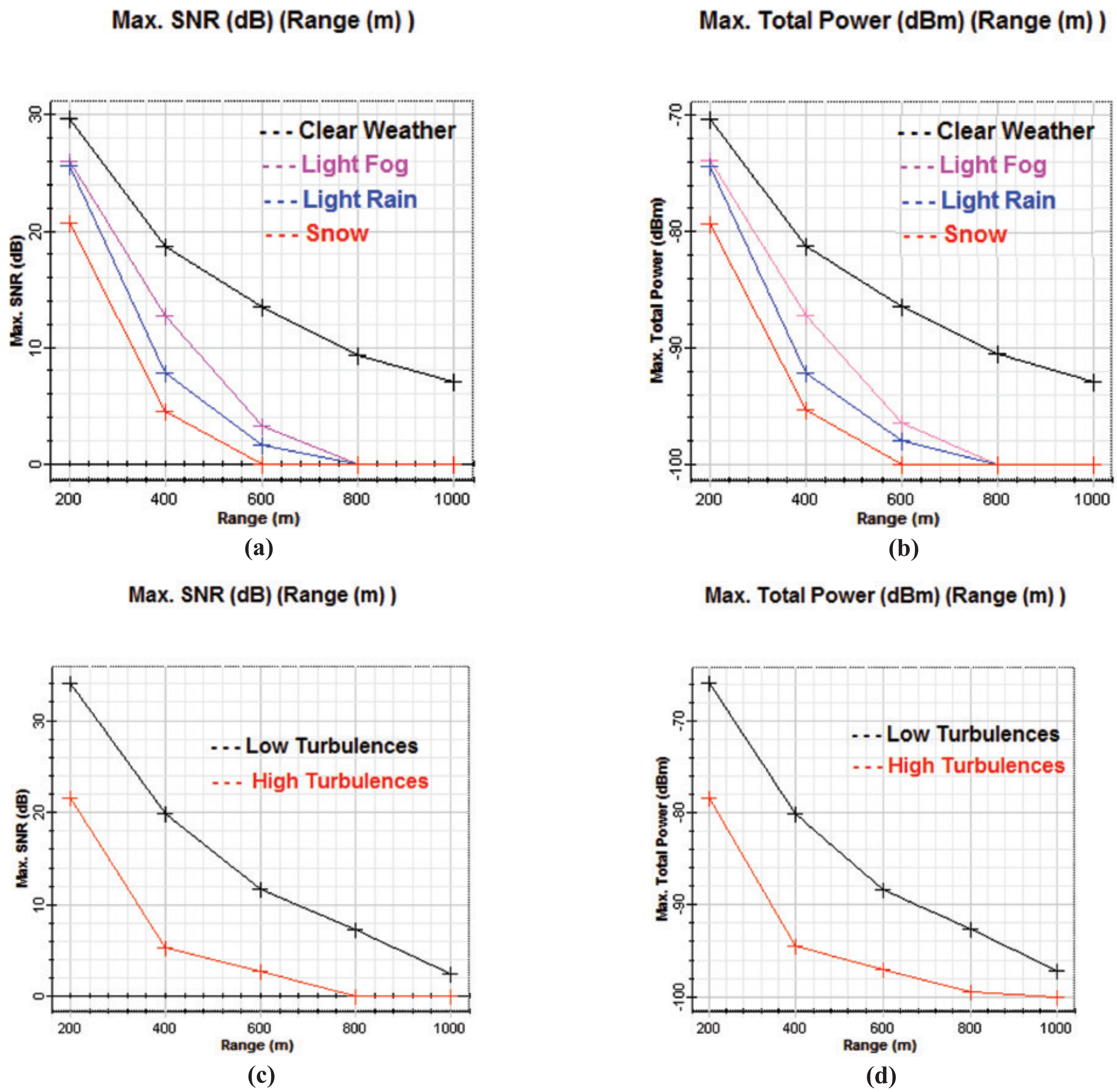

Fig. 3: SNR and received power against FSO as terrestrial link under atmospheric turbulences

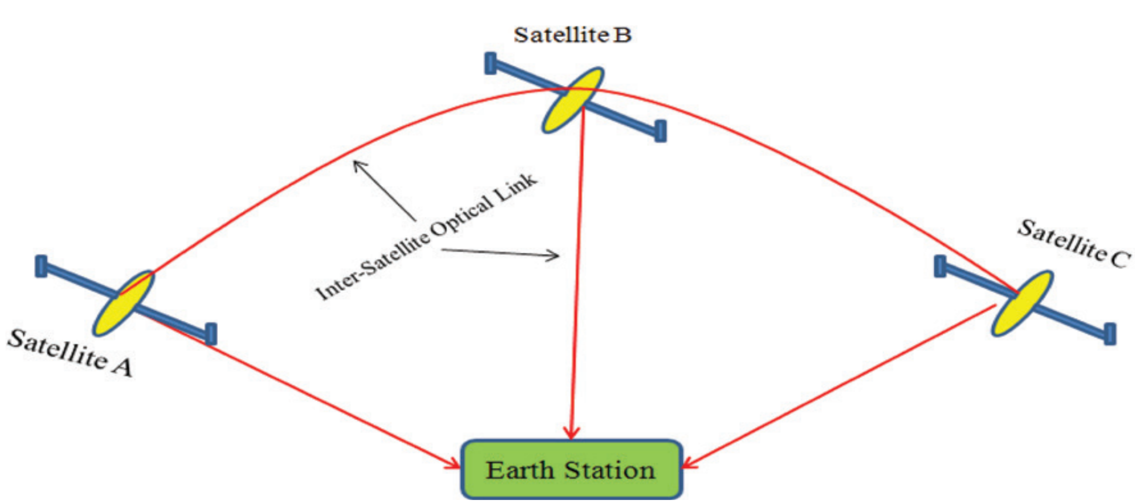

Fig. 4: FSO as inter-satellite communication link

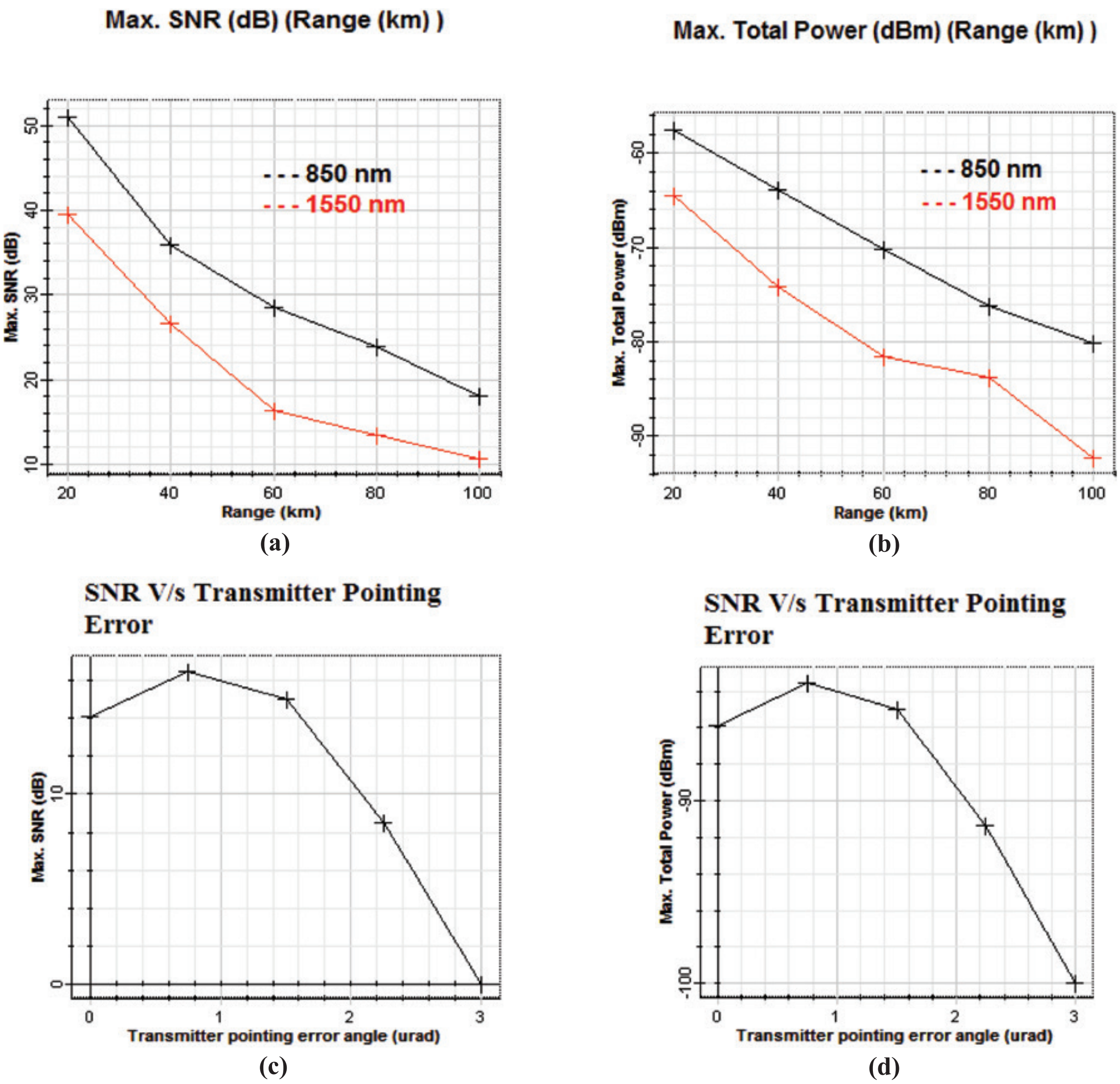

Fig. 5: SNR and received power against FSO as inter-satellite link

The basic link equation [41] for the inter-satellite is given by the following relation:

$$P_R = P_T \mathbf{N_T} \mathbf{N_R} \left(\frac{\lambda}{4\pi Z}\right)^2 G_T G_R L_T L_R \tag{6}$$

where P_R defines the received power, P_T defines transmitted power, $\mathbf{N_T}$ is the optical efficiency of the transmitter, $\mathbf{N_R}$ is the optical efficiency of the receiver, λ is the wavelength, Z is the distance between the transmitter and receiver, G_T and G_R are the gain of the transmitter and receiver telescope and L_T and L_R are the pointing loss factor of transmitter and receiver respectively.

Many researchers have reported the development in FSO link for inter-satellite applications [42–45]. In a experiment [42], the authors has derived the probability density function of optical intensity in the receiver plane and proposed scintillation indexed for the identification of intensity fluctuation which are helpful in designing of inter-satellite links. In another experiment [43], the authors have investigated the channel capacity for inter-satellite optical links to realize the high speed communication and proposed an optimum input distribution by maximizing mutual information for inter-satellite optical communications in the presence of random pointing jitter. In another experiment [44], the authors have reported enhanced improvement in inter-satellite link by implementing the square root module with data transmission rate of 2.5 Gbps. In another experiment [45], the authors used the series of micro ring resonators and an add/drop filter to generate a large bandwidth signal as localized multi wavelength for inter-satellite communication.

Data simulations were performed for FSO for inter-satellite communications using OptiSystem. Fig. 5 depicts

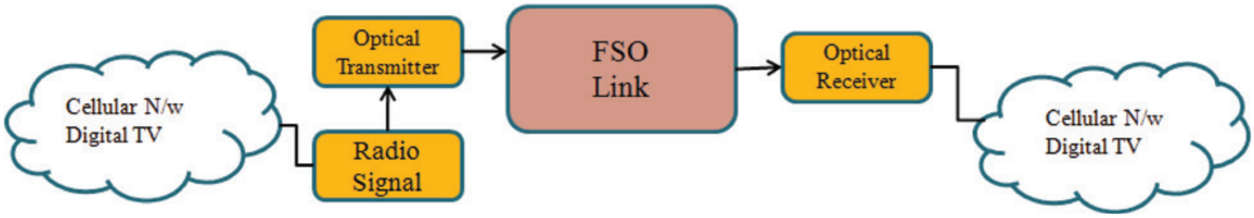

Fig. 6: Radio over free space (Ro-FSO)

the SNR and total received power for the FSO as an inter-satellite link. The bandwidth for inter-satellite is investigated by transmitting a 1 Gbps data using again NRZ modulation technique. It is revealed from the Fig. 5(a) and (b) that an improvement of 10 dB in SNR and –9 dBm in received total power is noted after the transmission through inter-satellite link having a span of 20 km when the link is operated at 850 nm wavelength compared to the 1550 nm. The SNR and received power degrades when the pointing error is increased as shown in the Fig. 5(c) and (d).

4 Radio over free space optics link

In wireless networks, users require instant and efficient connection to access various services at any time from any location at a low cost. The advantages of FSO in terms of free licensing and high speed makes FSO a compelling candidate for future wireless networks. In some geographical areas where current wireless radio technology are inaccessible such as in-building, hilly terrains and underground, FSO technology may be integrated with radio technology to promote more rapids deployment of a more ubiquitous wireless service and cellular architecture. Ro-FSO can also be used in rural areas with low populations where it may not be cost-effective to establish radio infrastructures.

In an experiment [46], optical modulators are investigated for transporting the radio signals over free space optics. In another experiment [47], the performance of DWDM-Ro-FSO system is evaluated by transmitting radio signals over FSO having a span of 1 km. The analogue of the Ro-FSO system is shown in the Fig. 6. The transportation of radio signal over free space is known as radio over free space. It harnesses the advantages of both FSO and RoF technologies, which makes it a commendable technology for future ubiquitous wireless networks. The RF link can also be further used as a backup link for FSO under the strong effect of atmospheric turbulences on ground communication.

5 Conclusion

In this paper, simulations of 1 Gbps data transmission are shown through both FSO as terrestrial and inter-satellite links under various atmospheric noises. The integration of radio signals to FSO leads to the reduction of deployment cost for the wireless operators and addresses the "last mile" bottleneck in access networks. Nevertheless, future work should alleviate the effects of atmospheric turbulence to achieve higher data rates to realize Ro-FSO as a promising technology for future wireless networks.

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