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CHAPTER 1

INTRODUCTION TO FREE SPACE OPTICAL (FSO) COMMUNICATION

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1. 1 Introduction

The evolution of wireless communication applications over the past decades is enormous, driven by the ever increasing number of wireless broadband internet, mobile phones, smart devices, social web, gaming, and video-centric applications. The number of end users is grown by about 30-40% per year i.e., from 16 million to 3.6 billion in 1995 and 2016 [1,2], which has put a tremendous pressure on the network infra-structure thus forcing the service providers to upgrade their current systems for higher wireless access data rate and improve quality of service. Until now, the radio frequency (RF) based wireless systems have been the prominent and mature technology in a range of fields including wireless local area network (WLAN), global positioning system (GPS), RF identification (RF ID) systems, home satellite network, etc. [3]. In addition, the third and fourth generations (3G/4G) wireless networks have experienced a growing increase in the data traffic due to the wide-spread use of smart devices any-time any-where. The volume of mobile and wireless users and thus the data traffic are predicted to increase a thousand-fold over the next decade [4], thus resulting in the mobile spectrum congestion (i.e., bandwidth bottleneck) at both the backhaul and last mile access networks [5]. Of course, the situation is going to get even more challenging by the introduction of 5G and beyond wireless technologies.

However, operators consider alternative technologies to overcome the spectrum congestion in certain applications, where the RF based technology cannot be used or is not suitable. For example, in highly populated indoor environments (train station, airports, etc.), and ‘the last mile access’ network, where the end user, using the RF based wireless technologies, do experience lower data rates and low quality services due to the spectrum congestion (i.e., bandwidth bottleneck). Thus ensuring the most efficient and effective utilization of the RF spectrum in dense-traffic areas. This could include point-to-multipoint links in areas where spectrum for the conventional point-to-point links is becoming scarce and costly. The microwave, millimetre wave and optical fiber based technologies will continue to retain their importance as a backhaul bearer. To increase the bandwidth and capacity, service providers are considering moving to higher frequencies (i.e., 40 and 80 GHz bands), but at the expense of reduced transmission coverage, which has adverse effects on the cost (i.e., deployment, site rental, maintenance, equipment, etc.).

In a perfect scenario, all end users should have access to the optical fibre based backbone network with an ultra-high capacity, to benefit from truly high-speed data communications with a very low end-to-end transmission latency. Fiber optical communication systems as the most reliable and high bandwidth transmission technology meet the bandwidth requirements and high quality of services mostly at the backbone network with the potential to move in into the last mile and last meter access networks. However, the cost and challenges associate with installation of optical fibre particularly in rural areas as well as maintenance of such a network is rather high, therefore is not considered for the last mile access network [6]. Of course, for environments where deployment of optical fibre is not economical a combination of satellite communications and optical fibre communications technologies would be the most suitable option. However, this could also be quite costly and therefore may not be feasible in the long run.

1.2 Free Space Optics

The demand for high bandwidth and secure communication is increasing in future. Therefore, free space optical (FSO) wireless communications technology could be one possible alternative option to the RF technologies that can be adopted in certain application to un-locked the bandwidth bottleneck issue more specifically in the last mile access networks, between mobile base station in RF cellular wireless network, and as of the radio over optical fiber [7-9]. During the last decade, we have seen a growing research and development activities in the FSO communications in the field of high data rates wireless technology applications as well as the emergence of commercial systems. The principle reason behind the increasing popularity of FSO is its capability to meet the user's ever increasing demand for bandwidth, which is not possible with the existing RF based wireless technologies [6,10].

Note that, most FSO systems are based on the line-of sight (LoS) intensity modulation/direct detection (IM/DD) laser (single or multiple wavelength) transmission, which offering similar capabilities as optical fiber communications with attractive features including (i) huge bandwidth; (ii) no licensing fee since the optical spectrum bands lies outside the telecommunication regulations; (iii) inherent security at the physical layer for mostly the point-to-point link configurations; (iv) low cost of installation and maintenance [10-13]; (v) lower power consumption; (vi) immunity to the RF-based electromagnetic interference [8-10]; (vii) back-bone network compatibility, where FSO is operating at optical transmission windows of 850, 1300 and 1550 nm, which are compatible with optical fiber back bone networks, as well as 10 μm [14]; and (viii) no or very little inter-channel interference due to a narrow laser beams, which guarantees high spatial selectivity. FSO systems employing heterodyne detection techniques are also used in order to increase the sensitivity of the receiver and improve the robustness of the systems against channel induced impairments [15]. Some of the key features of FSO links are as follows:

(i) The global information and communications technology is responsible for 2 - 10 % of the global energy consumption according to the report smart 2020 [16]. The global warming and the existing concern to reduce the power usage is a critical motivation to replace RF links with FSO in certain applications since the FSO technology is potentially green in terms of energy consumption compared to RF [17,18].

(ii) At the present time RF-based wireless technologies provides 1 to 2 Mbps for unregulated 2.4 GHz ISM bands [19], 20 Mbps 875 Mbps at 5.7 GHz 4G mobile and 60 GHz millimetre wave (MMW), respectively [20]. Potentially FSO can provide bandwidth as large as 2000 THz, which is far beyond the maximum data rate of RF technologies [21,22]. In addaition, FSO offers dense spatial reuse [23].

(iii) A review survey conducted with the operators in Europe and USA companies concluded that FSO is much faster to deploy than any other fixed communication technology [23]. Moreover, the speed of installation of FSO is in hours as compared to the RF wireless technology which can take up to months [10,14].

(iv) The main advantage of the confined beam of FSO communications is the ability to provide a significant degree of covertness. A malicious eavesdropper would need to within the LoS transmission path in order to intercept the light and therefore access the information [24]. This makes the interception almost impossible as the eavesdropper's antenna is also likely to cause link outage for the intended recipient due to beam obstruction. Jamming an FSO is also difficult because of the nature of optical beam is narrow and also invisible [25,26].

1.3 FSO Applications

The FSO technology with data rates ranging from multi-Gbps to a few Mbit/sec or less, over typical link spans of a few micro-meters to hundreds of meters have been adopted for civilian applications 27,28] including:

- **In-chip optical interconnections** - with path lengths ranging from hundreds of microns up to ~ 1 cm.
- **Last meter indoor communications** - with path length <100 m - usually using infrared and visible lights.
- **Last mile access network in rural areas** [29] – The bandwidth bottlenecks within the access network is a major issue, which has been depriving the end users with sufficient amount of bandwidth in order to meet their requirements [23]. A number of technologies (wired and wireless) have been developed to bridge the last mile. With the increasing level of deployment of fibre optic technology such as the Ethernet passive optical networks (EPON), the bandwidth bottleneck is being shifted towards the last mile access network. EPONs are designed to carry Ethernet frames at gigabit Ethernet rates but are not cost effective [30,31]. However, wireless networks capable of offering gigabit per second data rates in the last mile access network still have bandwidth limitations, thus enabling the end users to have a full access to broadband internet [32]. This problem is more acute in the rural areas where access to high-speed broadband using the existing technologies is rather limited [33,34]. In such scenarios the FSO technology could offer gigabit Ethernet to the end users. FSO can replace optical fibre access technologies such as fibre to the home (FTTH) in order to provide connectivity between in-building networks and to broadband and backbone data networks [35,36].
- **LAN-to-LAN inter-connectivity- [27,37] and electronic commerce [38]** – provides high-speed, flexibility and high security connectivity for campus and metropolitan applications.
- **Audio and video streaming** [39] – for video surveillance and monitoring, as well as live broadcasting of sporting events, in emergency situation [40] etc.
- **Unmanned aerial vehicle (UAV) and high attitude platforms [27,41]** – for monitoring traffic and disaster areas, or broadcasting vital data to the emergency services etc.
- **Disaster and emergency relief network** – where the existing communications networks is no longer operational and therefore FSO systems can be quickly used to establish communications links for emergency services.
- **Inter-satellite communications, ground to/from satellite communications, and deep space communications**- Numerous ultra-long-haul outdoor optical wireless systems have been proposed and implemented in a wide range of applications including terrestrial, earth-to-satellite and satellite-to-earth, earth-to-high altitude platform, intersatellite, and interplanetary communication links [42-45]. Major technical advances in the field of adaptive optics and beam acquisition/tracking, which are the critical and importance functions in ultra-long-haul outdoor FSO links

have enabled the deployment of tractable broadband outdoor optical wireless communications systems [46,47]. FSO satellite network can provide a high-bandwidth optical wireless network access to the end users since the satellites can cover large areas on the earth.

- **Underwater communications networks** - Is suitable for various applications like undersea explorations, environmental monitoring, disaster prevention, distributed tactical surveillance (unmanned underwater vehicles), and underwater sensors to monitor the surveillance, targeting, and intrusion detection [48]. FSO can provide broadband communications for underwater wireless sensor networks such as to transmit video streams or downloads a large burst of stored data in a brief time slot. This is very crucial when the data is required from a specific location or within a short polling time slot.
- **Hybrid FSO/RF communications** - FSO and RF communications can be realized as a complementary scheme in order to overcome the limitations of both technologies and achieve 99.999% link availability under all weather conditions [48-50]. The scattering effects due to fog/smoke and atmospheric turbulence degrades the bit error rate (BER) performance of a FSO link. Note that, for a FSO link at 830 nm the measured attenuation due to fog is 37 dB/km at a visibility of 200 m, whereas for a 58 GHz RF link it is 3 dB/km [51]. However, with rain the RF link experience attenuation of 17 dB/km at a rain rate of 40 mm/hr, whereas for a FSO link at a wavelength of 830 it is 2 dB/km [51]. Note that, the probability of occurrence of fog and rain simultaneously is very low [52]. Hence, the RF link provides a back-up link to FSO in fog conditions [53]. Table 1.1 summarises the differences between FSO and RF communications.

Table 1.1 Comparison between FSO and RF communication systems.

Parameter	FSO Link	RF Link
Data rate	Up to 10's Gbps using multiple wavelength	< 1 Gbps
Devices size	Small	Medium - Large
Bandwidth	License free	Required for most frequency range
Security at the physical layer	Very high	Very low
Network architecture	Scalable	Non-scalable
Cost	Moderate	Low to moderate
Link performance effects	fog, Atmospheric turbulence misalignment or obstruction	Multipath fading, rain, interferences
Transmission range	• Short to medium • Long for ground to space and space to ground	Long
Noise limitation	Background light	Other sources
Installation complexity	Low	Medium

1.4 Key features and advantageous

In most cases, the FSO modules, which are compact in size, are installed on the tall buildings, connected from rooftop-to-rooftop, window-to-rooftop or window-to-window. In practice, using a hybrid link the availability of five nines (99.999 %) is reported [19]) as well as to reduce the cost of the complete system. The cost effectiveness of FSO system compared to the RF system is more obvious, when the RF system is supposed to deliver the same high data rate connection service [54-58]. With the emergence of powerful and efficient optoelectronic components and advanced communication techniques, current states-of-the-art FSO prototypes have demonstrated transmission data rates of 10 Gbps over a range of few kilometres, which are commercially available with improve the link quality (e.g., it is desirable to achieve ideal 100 % link availability in all weather conditions [59], a data rate of 7.5 Gbps up to distance of 40 km [61], and up to 1.6 Tbps over a 80 m single outdoor link based on the dense wavelength division multiplexing technique [61-63].

One option adopted in order to increase the spectral efficiency (i.e., total data rate) and performance of FSO is to adopt spatial division multiplexing (SDM), where multiple independent data carrying optical beams simultaneously are transmitted over the same free space channel [14,16]. Note, a sub-set of SDM use mode division multiplexing, where orthogonal modes from a model basis set are used for transmitting each optical beams [64], in order to ensure multiplexing, transmission and demultiplexing of different beams with little inherent crosstalk [65]. In [66] an experimental demonstration of 400 Gbps FSO transmission using mode division multiplexing was reported.

Note that, SDM can provide a simple solution to the major setbacks in designing multiple input multiple output (MIMO) systems, i.e., reduced interchannel interference and improved inter-antenna synchronization [16,19]. Space shift keying (SSK) - a special case of SDM [19] - exploits only the spatial positions of transmitters to encode the information bits thereby trading the receiver's complexity off against the data rate. More recently, quantum key distribution has been recognized as the only approach so far to realize secure communications, which can be implemented in FSO links [67-69]. In [70], a high-speed (120 Mbps) four-state continuous-variable quantum key distribution system, based on wavelength-division multiplexing, polarization multiplexing, and orbital angular momentum multiplexing was investigated under atmospheric turbulence.

In order to improve link availability (i.e., 99.999 % availability) hybrid FSO-RF systems are proposed and adopted. Indeed, the gap between the backbone and a last mile access network can be filled by adopting the hybrid RF-FSO technology, thereby enabling multiplexing of a number RF users via a single FSO link. More recently, a hybrid dual-hop amplify-and-forward based RF-FSO link have been considered [71-73], which offers a strong option for the last mile access network connectivity. For such links, the system performance has been investigated assuming Rayleigh and Gamma-Gamma fading on the RF and FSO links, respectively [71], and considering the effect of pointing error [74]. Note, the hybrid FSO-RF system performance can be increased by adopting relay selection approaches, such as the partial relay selection [76,77], the relay is selected based on the CSI of only one hop, in contrast the other relay selection approach requiring global knowledge of the CSI of all hops. In [78], a unified and general performance evaluation of a dual-hop amplify-and-forward based RF-FSO link with the relay selection strategy based on outdated CSI estimates is reported.

The FSO technology along with plastic optical fiber/ multimode fiber and indoor optical wireless communication links can also be used as part of heterogeneous optical networks to address the bandwidth bottleneck in communications networks, where ultra wideband RF signal at 60 GHz are transmitted over fiber (i.e., the radio-over-fiber (RoF)). Note that, RoF approach requires frequent electrical-to-optical and optical-to-electrical conversions and costly optical components. In addition, it is not very efficient in terms of optical bandwidth utilization since it transmits low-speed wireless data over a wide bandwidth optical channel

[80]. The FSO based heterogeneous optical networks can deliver high speed optical signal i.e., 40 Gbps and beyond to the end-user, thus providing high-bandwidth, and solving interoperability problem of future optical networks [80]. Furthermore, optical networking facilitates the operation complexity at the IP layer and thus reduce the connection latency and the cost to deploy and operate the networks.

1.5 FSO Networks

The LoS FSO based topologies can be classified into three categories of point-to-point, ring and mesh networks as shown in Fig. 1.1. The 1st topology is the most basic and most commonly adopted, which only requires two LoS FSO transceiver between two locations typically few hundred meters up to few kilometers (usually ≤ 4 km) a part. The 2nd topology is composed of more than two nodes offering improved network and traffic protection. However, it does suffer from the link failure, which can be resolved using the traffic loop back mechanism provided there is a monitoring mechanism to detect the fault as well as protocols to activate the loop-back mechanism, which is usually located at the physical layer near to the transceiver head or at the MAC layer [79]. To cover a longer and wider transmission span and area, the ring network can be linked up with another ring networks.

The mesh topology, which is capable of interconnecting multi-nodes, the communication links are scalable and expandable up to several kilometers-square, therefore is considered as the best solution to interconnect FSO nodes in different terrain. In addition, this topology offers flexibility in mounting the individual FSO module at different conditions as well as the best network and service protection, which is suitable as part of ad-hoc networks provided the LoS is maintained (i.e., high availability, connectivity, increased capacity, and network utilization) [80]. In this topology, one detecting a faulty node, the traffic is rerouted via an alternative path based on the routing algorithms. However, the drawbacks are complexity and increased maintenance cost (requiring traffic capacity, traffic routing, and traffic balancing). As in the ring topology network, this network needs thorough monitoring for fault detection, require traffic balancing so that all nodes deliver the acceptable performances, and also maintain the traffic priorities.

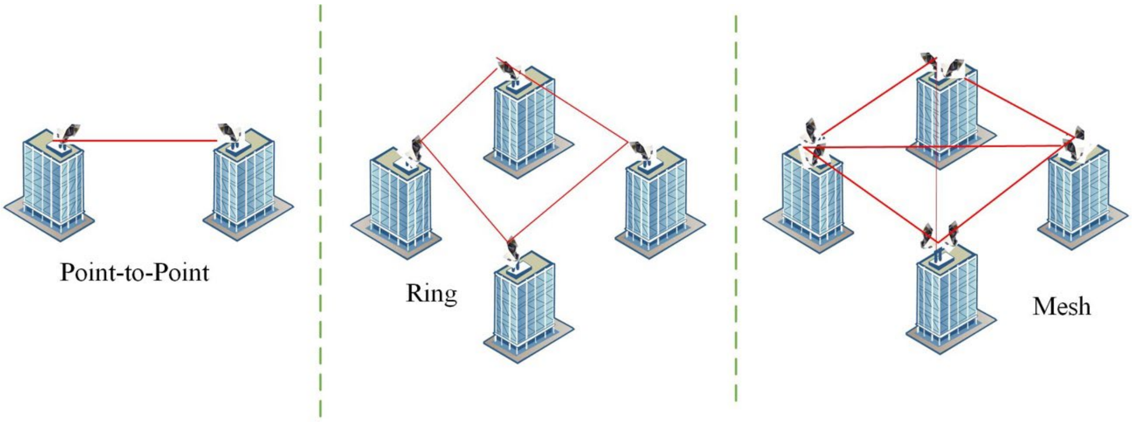

Fig. 1.1 FSO topologies

The basic concept of FSO communications is similar to RF communications in terms of data generation, modulation, transmission, reception, and processing of data. A typical IM/DD FSO link is shown in Fig. 1.2. Both the transmitter and the receiver must directly point to each other without having any obstruction in their path to ensure the communications link is always established. The unguided channel could be either space, seawater, or the atmosphere.

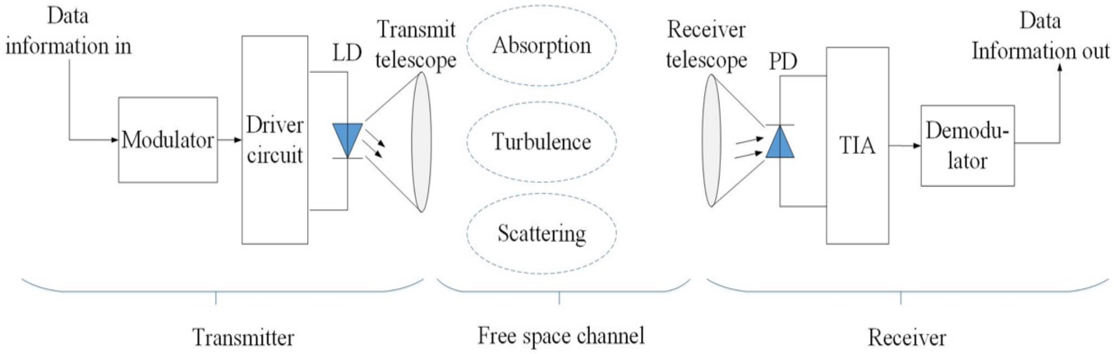

Fig. 1.2 The block diagram of an FSO communication system

The Tx composed of four main components of laser modulator, driver, optical source, and transmit telescope. Both laser diodes and light emitting diodes (LED) based transmitters can be used in FSO systems [81], where laser based FSO links are mostly used for high data rates (> Gbps) and long range transmission [82] and LED based FSO systems are used for low data rates and short range inter-building communications [83]. The IM laser beam is transmitted via the transmit telescope, which collimates and directs the optical radiation towards the receiver telescope at the other end through free space channel. The functionality of the driver is to regulate current flowing through the light source and stabilizes its performances as well as neutralizes temperatures and aging effects on the performance of the laser. While there are a number of modulation scheme that can be adopted in FSO systems, the most common modulation formats considered is the binary amplitude-shift-keying or widely-known as the on-and-off (OOK) due to its high bandwidth efficiency.

The non-return-to-zero (NRZ) OOK format is the most simplest followed by return-to-zero (RZ), which offers higher sensitivity compared to NRZ OOK [84] and with the clock frequency being part of the signal spectrum. However, in both NRZ and RZ based OOK long transmitted bit stream of “1” and “0” can lead to the loss of clock synchronization. This can be avoided by using Manchester coding, and pulse position modulations, the clock can easily be recovered, but at the cost of increased transmission bandwidth. OOK has become a dominant form of signalling because of the transmitter and the receiver hardware are relatively simple and fiber optics networks generally operate a high signal-to-noise ratio (SNR) with a lower dynamic range requirement and well controlled signal levels at the receiver [85,86].

In addition, line codes (i.e., 8B10B with 25% more bandwidth requirement than NRZ) can be used to maintain a constant short time average of the signal (i.e., the baseline) in order to reduce inter-symbol interference due to high-pass filtering at the receiver, and to recover the clock signal [85]. Alternatively, modulation can be carried out externally where the transmitted laser beam’s phase and frequency is modulated using the external modulator such as the symmetric Mach-Zehnder interferometer. Note, the transmit optics such as telescope or lens is used to focus the optical energy towards the receiver in order to minimize the divergence [86,87].

The commercial FSO systems can be classified into two transmission windows of 780-850 nm and 1520-1600 nm [88]. The transmission windows of 780-850 nm is preferable for FSO due to low cost, reliable, and high performance transmitter and detector components are readily available and are commonly used in networks and transmission equipment. Moreover, avalanche photodiode and a cheaper vertical-cavity surface-emitting lasers (VCSEL) can be used in this wavelength range offering modulation speeds beyond 3 Gbps [89]. On the other hand, the 1550 nm wavelength is well suited for free space transmission due to low attenuation (i.e., Rayleigh scattering), as well as the proliferation of high-quality transmitter and detector components. In addition, it facilitate higher transmit power, 50 times greater than 800 nm wavelength [40], due to lower eye safety requirements, thus enabling data transmission over longer distances. According to [88], laser beams at 1550 nm wavelength are more eye safety since the laser beam at the wavelength above 1400 nm is absorbed by the lens and the cornea, and thus there is no destructive focal point to create damage on the retina [61]. On the other hand, at 800 nm the retina could be permanently damaged as the collimated light beam entering the eye is concentrated by a factor of 100 000 times when it strikes the retina. Most of the optical devices are also compatible with 1550 nm. However, the trade-off are less receiver sensitivity and higher component cost.

At the receiver end, a large receiver telescope aperture is desirable in order to collect the uncorrelated flux of optical beams and focusing their average flux onto the photodetector. This is called aperture averaging; however, this will collect more background noise intrinsic to a wide aperture area [90]. Hence, an optical band pass filter is normally used to minimize the magnitude of the background noise. Compared to the transmitter, the receiver choice is much more limited. The two most common photodetectors used are PIN diode and avalanche photodiode (APD).Note, PIN based optical receivers are widely used in outdoor FSO links compared to APD, which shows reduced SNR by amplifying the ambient noise [91]. In addition, APD require a much higher bias voltages level (i.e., >30 V for InGaAs to 300 V for the silicon based APDs) [92].

The received optical beam is collected and focused by the receiver telescope to the PD, which converts the optical signal into an electrical form prior to being amplified by trans-impedance amplifier, and demodulator. Semiconductor photodiodes (i.e., p-i-n and avalanche photodiode) are usually preferable because of their compact size, relatively high spectral sensitivity, and a very fast response time (rise and fall time) [12,93]. Normally, an optical band filter is placed before the PD to minimize the effects of background radiation [94]. Following amplification, the original electrical signal is reconstructed by the demodulator from the time-varying current in spite of the channel-induced degradation and the noise added at the receiver. The design of demodulator is depends on the nature of the signal (i.e., analog or digital) and the modulation format [14,95]. Prior to the information is recovered, post detection processor is used where the necessary filtering and signal processing is done to guarantee a high fidelity data are carried out. With IM/DD based FSO communication systems, effective detection techniques are needed to mitigate the channel induced performance degradations [96-99]. There are a number of detection schemes including.

(i) **A maximum-likelihood sequence detection (MLSD) scheme** - which outperforms the maximum-likelihood (ML) symbol-by-symbol detection scheme provided the temporal correlation of turbulence τ_0 is known [96]. However, for $\tau_0 \cong 1 - 10$ ms the computational (i.e., implementation) complexity for MLSD at the receiver is relatively high. To overcome, this issue suboptimal MLSD schemes based on the single-step Markov chain (SMC) model could be adopted [100], which require perfect channel state information at the receiving end. Provided, τ_0 is known, a pilot symbol, periodically added to the data frame in pilot-symbol assisted modulation (PSAM), could be used to mitigate the effects of channel fading, but at the cost reduced system throughputs [101].

(ii) **The decision-feedback (DF) detection scheme** – a ML sequence receiver with no requirement for the knowledge of CSI, channel distribution and transmitted power where detection is based on the prior knowledge of previous decisions made and on the observation window over τ_0[102]. However, this scheme has a drawback where the value of τ_0 depends on the data stream, where one needs to use a fast multi-symbol detection scheme based on block-wise decisions and a fast search algorithm [103]. The main drawback of this method is trade-off between the throughput and performance as well as being too complex to implement.

(iii) **A blind detection scheme** - where there is no CSI has been proposed considering the case for background-noise limited and a sub-optimum ML detection based receivers [104] and [105], respectively but poor performance over a small observation window.

(iv) **Differential signaling (DS)** - which utilizes a pre-fixed threshold level under various channel conditions (rain, turbulence, etc.), and it does not require CSI and neither has extensive computations at the receiver [106]. Note that, in this scheme (a) the system throughput is not reduced since no pilot signals or training sequences are used; (b) offers simplified detection procedure; (c) mitigates for the background noise (i.e., the ambient noise) at the receive [107].

(i) **Spatial diversity and multiplexing [98,99]** - This technique offers substantial link performance improvement in spatially uncorrelated channels by employing multiple apertures at the transmitter and/or the receiver that are sufficiently spaced as in single-input multiple-output (SIMO), multiple-input single-output (MISO) or multiple-input multiple-output (MIMO) systems [12, 108,109,110]. In FSO systems, the most commonly adopted spatial diversity techniques are repetition coding, which achieves transmit diversity by simultaneous transmission of the data via all transmitters, and orthogonal space time block codes. Note that, in IM/DD FSO links repetition coding outperforms orthogonal space time block codes [111,112]. Multiplexing of multiple orbital angular momentum (OAM) beams is another possible approach for increasing system capacity (up to 100 Tbps combined with wavelength division multiplexing) and spectral efficiency in FSO systems [113].

(ii) **Relay-assisted or multi-hop FSO** – a powerful fading mitigation tool as an alternate option in realizing the spatial diversity scheme advantages, which is based on the broadcast nature of the RF wireless technology [114-118].An all-optical FSO relay-assisted system can be adopted to mitigate the destructive effects due to distance dependent atmospheric turbulence induced fading [119]. It offers an efficient and low-cost solution compared to the MIMO systems as it does not need an additional transmitter and receiver aperture.

(iii) **Hybrid FSO/RF** – the hybrid FSO/RF link refers to a single antenna unit with dual functionalities at the transmitter and receiver for both optical and RF signals transmission [120]. The key features of the hybrid system are (i) reduced power consumption and costs, which is achieved by means of incorporating the optical aperture as part of the RF antenna and only utilizing FSO or RF path at any given time depending on the weather conditions; (ii) link alignment, where both FSO and RF could be used to establish the link alignment and maintain it via auto-tracking system within a certain degree; (iii) high link availability, which ensures full link availability under all weather conditions with higher data rates capability; and (iv) installation cost and complexity, which is much lower in the hybrid antenna based wireless link than the dual antenna base systems [118-124].

FSO systems with coherent receivers and the benefit of adopting spatial diversity techniques are extensively reported in the literature [15, 125,126]. Coherent detection (homodyne and heterodyne) is employed in less reliable FSO links in order to increase the sensitivity of the receiver and improve the robustness of the systems against channel induced impairments such as turbulence [15,127]. In homodyne based detection, which uses a local optical oscillator synchronized to the transmitted optical signal carrier frequency, the optical signal is directly demodulated to the baseband. However, optical synchronization is a bit unstable in practice, therefore heterodyne detection is adopted, which simplifies the receiver design by converting the optical signal back into an electrical signal with an intermediate frequency followed by a phase noise compensation technique for the IF signal phase noise tracking.A FSO link with a coherent receiver, which mitigates the degradation performance caused by phase fluctuations due to turbulence phase compensation schemes, have been proposed [128,129].

Note that, in coherent FSO systems with relatively higher system complexity compared with IM/DD offer features such (i) the signal dependent shot noise limited SNR, provided the optical local oscillator has a sufficiently high power; (ii) the extraction of phase information allows for a large number of modulation schemes compared IM/DD; (iii) excellent background noise rejection compared to IM/DD; and (iv) higher sensitivity, and improved spectral efficiency [130,131].

Note, in LoSFSO systems links, the link performance highly depends on the number of received photons. For DD based FSO systems, there is an optimal receiver's field of view to ensure improve link performance. If the radial angle-of-arrival of the optical signal is within the receiver's field of view, then the entire received optical beam will be collected at the receiver. However, if the receiver's field-of-view is small, then the number of received photons is strongly related to the turbulence induced angular spread, which needs considering in order to properly investigate the performance of FSO systems. Thus, the receiver's aperture acts as a spatial filter only collecting photons within its field of view. In [130], the benefit of coherent detection over DD in the presence of angular spread was investigated. Moreover, spatial diversity receivers, which are able to significantly improve the performance of atmospheric optical systems, are discussed in detail.

In optical communications including optical wireless communications, where the transmitted data rates are very high, the bit duration is very short compared to the channel coherence time. Therefore, in a turbulence channel the FSO link performance is best measure by the outage probability instead of the most commonly used bit error probability [125]. Note that, outage occurs when the error probability is above a threshold level, which indicates how often the link performance falls below the given threshold level.

1.6 Factors Affecting FSO Systems

There has been tremendous technical advancement of available components such as laser/LED transmitters, high sensitivity optical receivers offering extremely high bandwidth, efficient modulation techniques, improvement in low power consumption, weight, and size. In spite of many such technological development, the major limitation of FSO communications performance is the atmosphere conditions. The terrestrial LoS FSO link operating in the troposphere layer will experience a medium, which is continuously changing in chemical composition, humidity, pressure, temperature, and air movements. As a result, the FSO link performance is hampered by the atmospheric channel, which is highly variable, unpredictable and vulnerable to different weather conditions such as such as smoke, fog, haze, sandstorm, low clouds, snow, rain, atmospheric turbulence and pointing errors [1, 29,132], which may result in noticeable distance related power loss, and phase distortion at the receiving end [29,108,135]. With conditions of the earth's atmosphere, only a few atmospheric windows are suitable for FSO due to selective absorption by gases and water vapour [62]. The interaction with solid and liquid water particles in adverse weather can also generates signal fades which can lead to link outage [136]. Moreover, even in clear sky conditions, the turbulence induced by temperature and pressure gradients results into random fluctuations and loss of wave-front coherence [7]. Fog, haze, and dust induced atmospheric attenuation are critical and can result in link failure. Scattering due to collision of photons with the scatterers, which is wavelength dependent, leads to reduced light intensity over a longer transmission span. Physical obstructions due to tall buildings, flying birds, trees, etc., can temporarily block the propagating beam, this resulting in burst error or link failure; whereas geometric losses due to the beam spreading reduces the power level i.e., lower SNR at the receiver [137]. Absorption due to water molecules and carbon dioxide, reduces the power density of the propagating optical beam and therefore directly affecting the FSO link availability [138].

Atmospheric condition thus ultimately determines the FSO communication systems performance not only of terrestrial applications but also for space (satellite) links involving uplink-downlink communications (e.g., between ground and satellite, aircraft or UAV terminals), because a portion of the atmospheric path always includes turbulence and multiple scattering effects. There has been many research published during the last two decades on the subject of effects of atmosphere on optical communication channel and therefore are not repeated in this section. Interested readers can review them for understanding the details of the atmospheric channel for establishing communications between a transmitter and a receiver.

The FSO link visibility, attenuation in dB/km, and effective link range for a FSO system under various weather conditions are discussed [12,139]. For telecommunication applications, FSO systems will need to meet very high availability requirements. For example, carrier-class availability is considered to be 99.999% ('5 nines") for very high data rate communications. This reliability of 99.999% is equivalent to the link availability as the percentage of time over a year that an FSO link will be operational is the same as "down 5 minute/year". The FSO link ranges in the worst measured conditions for fog, snow and rain in order to extrapolate 99.999% availability link ranges, as well as actual 99.999% link ranges for Phoenix, San Juan, Las Vegas and Honolulu are given in [139].

1.7 FSO Link Reliability

The connection in a FSO system is accomplished by means of a narrow optical beam with low divergence. For a successful and reliable installation of optical link, it is therefore necessary to know the steady parameters for standard atmosphere and statistical character of the weather in a given locality. The performance of a FSO communications system is generally quantified by the "link margin" (LM), which is defined as ration of the signal power received to the signal power required to achieve a specified data rate with a specified acceptable probability of error. The LM calculation is therefore essential in order to design an acceptable system. The atmospheric conditions affecting the FSO link performance needs to be considered in the calculation. A link budget model, which includes dependence on the atmospheric channel and on the transmitter and the receiver [9,140-142], will aid designers in optimizing the FSO base station main parameters in order to be able to establish a data link with adequate performance. The link budget includes all average losses of optical power P_t [dBm] transmitted by the laser source, the received power P_r [dBm], receiver sensitivity N_b [dBm] and propagation loss L_p [dBm]. If we express the link margin (LM) in dBm, then we can write [9]:

$$LM = P_t - L_p - N_b \tag{1.1}$$

The LM value shows how much margin a FSO system has at a given range to compensate for scattering, absorption (due to fog, snow and rain) and scintillation (turbulence). A simple calculation shows that, using a laser with a transmit power of 30 mW, detector sensitivity of 25 nW, mis-pointing loss of 3 dB, optical loss of 4 dB the FSO link margin is estimated as 54 dB. It is shown that, for this link budget the FSO range even in the heaviest fog of 350 dB/km attenuation, which corresponds to 99.999% link availability, is still possible up to 140 m range.

We can define the dynamic range as the interval of acceptable power in which the link function is guaranteed with a definite error rate. The receiver is saturated when $P_r > P_s$ (a specified saturation value), and the required signal-to-noise ratio is not provided when $P_r < N_b$. Link reliability is quantified by the availability, which is the percentage of time T_{av} (%), when the data transmission bit rate is more than its required value. The link availability can equivalently be defined as the probability that additional power losses L_A caused by atmospheric effects (including absorption and scattering) are less (in dB) than the LM, which is defined as:

$$T_{av} = 100\,\% \cdot \int_{0}^{\alpha_A \lim} p(\alpha_A) \cdot d\alpha_A \qquad (1.2)$$

where probability density $p(\alpha_A)$is the probability density of an attenuation coefficient α_A (dB/km), L is the range, and the limiting attenuation coefficient value is given by:

$$\alpha_{A_{LIM}} = LM(L).1000/L \qquad (1.3)$$

$p(\alpha_A)$can be determined from long-time monitoring of the received signal level from a real measuring link, or using the data collected over a local area in the past for a long time. In practical network design, the concept of link availability in presence of atmospheric turbulence is an important consideration. In many FSO systems, an automatic tracking systems are used so that pointing errors are not taken into account in defining the link reliability.

Practical solution to extend the high availability range can be (i) hybrid FSO/RF communications system [120,78]; and (ii) optical network topologies employing relayed FSO links [9] in order to extend the 99.999% link rank range to longer distances so that the system will open up a much larger metro-access market to the carriers. To evaluate a FSO as an access technology for a particular location and link range, it is very useful to estimate these availabilities of the link. Enterprise-class availabilities can also extend the possible FSO link ranges to much longer distances depending on the geographical locations. The researchers have suggested that for high reliability, the optimum network architecture is a meshed network, because it combines the advantages of ring and star architectures.

A reliability analysis of FSO communications link using aberrated divergent rectangular partially coherent flat-topped beam is been reported in [143], which is based on numerical values for power-in-bucket (PIB), SNR and BER considering atmospheric losses due to absorption, scattering and turbulence. Reliability of FSO links including laser link stability can be improved using auto-track subsystems in presence of different beam divergences considering the atmospheric effects including absorption, scattering and turbulence [144]. An innovative approach based on all-optical relaying technique to mitigate the degrading effects of atmospheric turbulence-induced fading by relaying data from the source to the destination using intermediate terminals [27,71,97,114,119]. The proposed techniques of optical amplify-and-forward relaying and optical regenerate-and-forward relaying were applied to multihop

FSO systems in order to extend the maximum accessible distance for high data rates FSO systems. These techniques thus improved the reliability of the FSO system. Reliability of optical communication system is also discussed using polarization shift keying modulated FSO systems [12,145]. There are other techniques to improve the reliability of the FSO systems such as Hybrid FSO/RF communication using channel coding, soft-switching hybrid FSO/RF links using field-programmable gate arrays, modulation schemes combined with LDPC forward correction scheme, and multipath diversity [48, 71, 73, 120]. Optimization of FSO-based network for cellular backhauling in order to improve reliability is achieved by introducing a novel integer linear programming model [146].

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