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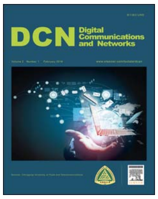

A survey of free space optical networks[☆]

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ABSTRACT

Free Space Optical (FSO) networks, also known as optical wireless networks, have emerged as viable candidates for broadband wireless communications in the near future. The range of the potential application of FSO networks is extensive, from home to satellite. However, FSO networks have not been popularized because of insufficient availability and reliability. Researchers have focused on the problems in the physical layer in order to exploit the properties of wireless optical channels. However, recent technological developments with successful results make it practical to explore the advantages of the high bandwidth. Some researchers have begun to focus on the problems of network and upper layers in FSO networks. In this survey, we classify prospective global FSO networks into three subnetworks and give an account of them. We also present state-of-the-art research and discuss what kinds of challenges exist.

1. Introduction

Free Space Optical (FSO) networks, namely optical wireless networks, are wireless telecommunication systems that make use of free space as a transmission medium to deliver optical data signals at high bit rates. FSO research started in the 1960s. The National Aeronautics and Space Administration (NASA) Deep Space Optical Communications Project "is to develop key technologies for the implementation of a deep space optical transceiver and ground receiver that will enable greater than 10X the data rate of a state-of-the-art deep space RF system (Ka-band) for similar spacecraft mass and power [1]." The European Space Agency (ESA) started funding various FSO projects since the summer of 1977, aiming to develop high-data-rate laser links in space. Although optical wireless links provide high data rates, FSO communications have not prevailed so far in spite of a long investigative history. As new advances are made in optics and communication devices, there has been a renewed, increasing interest in analyzing and enhancing wireless optical links and adopting FSO technology for wireless access networks. Recently, successful experimental results [2] demonstrated the feasibility of FSO communications. Researchers at the German Aerospace Center demonstrated FSO data transmissions at 1.72 terabits per second across a distance of 10.45 km [3]. The FSO network could become a viable candidate for use in broadband wireless networks of the next generation.

Wireless communications have beneficial properties not found in wired communications, such as the lower deployment cost due to the lack of having to ditch and lay down cables, ease of construction of network topology, flexible maintenance of operating networks, and so on. Wireless communications also allow users of mobile devices to access the Internet at any time and many locations. For instance, IEEE 802.11 (Wi-Fi), Bluetooth, and IrDA are intended for short-range wireless data communications [4], while Long-Term Evolution (LTE) is for long-range wireless communication for both mobile phones and data terminals [5]. As the number of mobile devices continue to increase, leading to the establishment of ubiquitous networks, wireless communication services are now indispensable to many people, like water and electricity supplies. Therefore, the volume of data traffic carried on wireless networks is growing at an unprecedented speed. In addition, data sharing in various multimedia services, like AOD (Audio on Demand), VOD (Video on Demand), and P2P (Peer-to-Peer) stimulates the necessity of higher data rate networks.

To meet the high demand for wireless capacity, radio-based wireless communications have enjoyed widespread use to this point, but have limitations on scalability and bandwidth. For example, there are considerable technical problems in Wireless Local Area Networks (LANs), one of the major wireless access technologies, which limit the support of an ever-increasing volume of data services. In particular, wireless LANs suffer from (i) low end-to-end throughput due to the

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limitation imposed by raw channel capacity and forwarding load [6], (ii) high overhead of MAC protocols which further reduces the available throughput [7,8], and (iii) fairness issue and even interruption of flows that are hops away from an Internet entry point [6,9].

To this end, FSO networks are considered to be a strong supplementary option and provide an effective solution to these issues. Their advantages over radio wireless networks are outlined below. Detailed comparisons between radio and optical wireless communications are found in [10–13].

- Optical wireless links provide high data rates to support broadband data services. There exist commercial transceivers that support Gbps data rates.
- The optical spectrum is license-free. Therefore, there is no need to obtain permission to use the optical channels; considerable spectrum licensing fees can be saved comparing to other wireless Radio Frequency (RF) based technologies.
- Optical beams are immune to electromagnetic interference.
- Unlike RF signals, optical components are inexpensive and consume less power.
- Due to narrow beam and point-to-point transmission properties, spacial optical links have the desirable LPI/LPD (Low Probability of Intercept/Low Probability of Detection) properties.
- Light sources with the same specifications can be reused in overlapping deployment areas or rooms in the building since light beams cannot penetrate walls, resulting in negligible mutual interference.

Two main problems, however, have hampered the practical deployment of wireless optical networks. The first problem is atmospheric turbulence, which makes link quality unreliable. Atmospheric turbulence affects the propagation of optical signals, leading to degraded performance directly under various forms such as SNR (Signal-to-Noise Ratio), BER (Bit per Error Rate), outage frequency, and so on. Weather effects on the connectivity of FSO networks were studied in [14], and it was shown that weather turbulence strongly affects the quality of FSO communication links. The second problem involves the PAT (Pointing, Acquisition, and Tracking) technique, which is extremely important in FSO systems because of its unguided narrow beam propagation through free space. Since an FSO transmitter is highly directional, FSO systems are often designed with a divergence of a few milliradians or less in order to concentrate the optical energy at a receiver. Each “optical transceiver” must be simultaneously pointed at each other for communication to take place. Because of its narrow beam property, precise alignment of the beams is required and PAT is non-trivial even for stationary nodes.

Research efforts have been concentrated on these critical problems, but usually for the single-hop, FSO link scenario, since nowadays, commercial transceivers are mostly used for bridging two remote stations. In the previous introductory papers, such as [11,15,13,16], it is shown that satisfactory link robustness and sufficient performance of a single link can be achieved by adopting an advanced PAT technique. As these single links are becoming reliable and durable, researchers can now start to focus on problems with network and upper layers in FSO networks [10,17,18].

In this paper, we present a survey of the network architecture, design factors, and research challenges for FSO networks. Recent research, covering topics from the physical layer to the network layer, is examined and discussed. We also provide a new vision for practical solutions to build reliable FSO networks. There have been several informative review papers on FSO networks, which present a broad view of FSO links and networks [15,11,10,19,18]. The objectives of [11,15] are to streamline the potential advantages, specific properties, and limitations, and present possible applications. Meanwhile, FSO networks have emerged recently as a viable option to become a part of the future broadband wireless networks. In [10,19,18], emphasis is placed on the exploration of extensive applications of FSO networks and corresponding challenges. However, FSO links have raised many challenging issues, which require a more comprehensive and up-to-date treatment. Additionally, we believe it is still beneficial to take a new look at the extensive range of FSO networks, from home to satellite, with a network perspective. Such as survey covers more recent work than the prior surveys, and will help researchers to identify new networking problems and develop effective solutions for FSO networks.

The remainder of this article is organized as follows. We first review FSO network architectures and provide a classification of FSO networks in Section 2. According to the scope of the network, FSO networks are classified into optical wireless satellite networks, optical wireless terrestrial networks, and optical wireless home networks. We then examine various important design factors in FSO networks in Section 3, including channel models, link availability and reliability models, automation, network topology design, Quality of Service (QoS) provisioning, product cost, and eye safety issues. We discuss research challenges in FSO networks in Section 4, including channel modeling, PAT, advanced hardware techniques, FSO networking, and transport layer issues. Section 5 concludes this paper.

2. Classification of FSO networks

Due to their high potential for a broad spectrum of applications, FSO networks have been investigated and employed for networks that span a distance from a few meters to over thousands of kilometers. As illustrated in Fig. 1, FSO networks can be roughly classified into three types: (i) Optical Wireless Satellite Networks (OWSNs), (ii) Optical Wireless Terrestrial Networks (OWTNs), and (iii) Optical Wireless Home Networks (OWHNs), according to the locations of optical transmitters and receivers and network range. It may not be easy to precisely delineate these networks, since various FSO subnetworks are integrated and operated as a whole, as shown in Fig. 1. We discuss each class of FSO network in detail in this section, and their characteristics are summarized in Table 1.

2.1. OWSNs (Optical Wireless Satellite Networks)

OWSNs are designed to provide high-bandwidth, optical wireless network access to end-users by making use of satellites, which cover large areas of the earth [20,16,19]. OWSNs establish a global space backbone network with optical links, since satellites can support any terrestrial residents regardless of topographical limitations as long as a Line-of-Sight (LOS) space path exists. Therefore, OWSNs offer high quality data services even to isolated areas such as an island, a remote

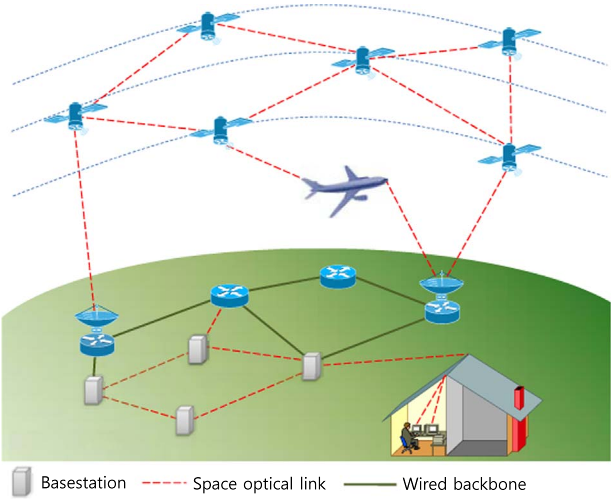

Fig. 1. The conceptual topology of integrated optical wireless satellite, terrestrial, and home networks.

Table 1
Characteristics of Optical Wireless Satellite, Terrestrial and Home Networks.

	OWSNs	**OWTNs**	**OWHNs (IrDA)**	**OWHNs (MSD, White LED)**
Location	Orbit	High/open place	Indoor	Indoor
Link distance	~84,000 kilometers	~10 kilometers	~a few meters	~tens of meters
Channel	Vacuum channel	Air turbulent channel	Weak turbulent channel	Weak turbulent channel
RX/RX FOV	Very narrow	Narrow	30 degrees	Wide
Performance limiting factor	Misalignment with long distance	Atmospheric turbulence	Limited power for eye and LOS blockage safety	Limited power for eye safety and multipath propagation
Hardware requirement	Precise PAT technology (Ex. Automatic steerable gimbals/beam)	Turbulence-resistant design (Ex. Spatial Diversity, RF/FSO, Hybrid architecture)	Lightweight, portable, and inexpensive component	Backbone between cells and MSD – holographic optical diffuser
Misc.	Long distance coverage and hard to maintain	Various impairment factors	Short-range point-to-point link	Exploiting reflection

farm, a ship on the ocean, an aircraft, and so forth. OWSNs consist of different types of free-space links including inter-satellite, satellite-to-air, and satellite-to-surface optical links. Inter-Satellite Links (ISLs) are designated for routing data traffic hop-by-hop through satellites toward a final destination satellite that has up-and-down links between the aircraft or a ground station on the surface of the earth. Usually such links have very high data rates ($\geq$10 Gbps). Thus, ISLs are used for inter-continental communications. The receivers can be stationary, such as those placed on top of buildings, mountains, towers, and so forth. The receivers can also be in motion, such as those installed in airplanes, a cruise ship, and ground vehicles.

Geostationary Earth Orbit (GEO: ~40,000 km altitude), Medium Earth Orbit (MEO: ~5,000–15,000 km), and Low Earth Orbit (LEO: ~1,000–2,000 km) satellites, along with FSO links, serve as commercially viable backbone nodes as is reasoned in [16]:

- OWSNs are an alternative for the current wired internet, especially for over-the-ocean communications that are largely carried through undersea optical fiber communication systems. OWSNs do not need such communication infrastructure as undersea cables and easily overcome the obstacles of long distances.
- With OWSNs, broadband wireless services can be provided even for secluded areas without much difficulty. Internet users who are on a mobile platform or are remotely located from a town can be provided with broadband data communications, which are hard to achieve with traditional access network technologies.

Service providers and network architects, however, should consider well both economical and technical factors to ensure that OWSNs will be successful in commercial systems. This is because the initial investment in satellite systems is usually considerable, and the manual maintenance for unexpected defects is almost impossible once satellites are launched. Therefore, several design factors such as physical topology, link capacity, and routing strategy are critical issues that need to be carefully addressed [21]. There needs to be substantial efforts made in the investigation and development of robust and reliable satellite-based FSO systems [16].

Military organizations are also actively concentrating on developing OWSNs required for strategic and tactical operations. In May 2001, the U.S. National Reconnaissance Office (NRO) launched a Geosynchronous Lightweight Technology Experiment (GeoLITE) satellite to test laser communications. Furthermore, the U.S. Department of Defense (DoD) Military Satellite Communications (MILSATCOM) Joint Program Office has a plan to fully operate the Transformational Satellite Communications System (TSAT) in 2016 as an integral part of the Global Information Grid (GIG) architecture of the U.S. military [22]. The TSAT network will be an FSO backbone, using satellites supporting high data rates (tens of Gbps) for air-fighters, battleships, various ground troops, and so forth. The U.S. military also developed fundamental technologies such as the Steered Agile Beam (STAB), a technology meant to align the direction of an optical beam without any steerable hardware devices like gimbals, and the Airborne Laser Terminal (ALT), intended to operate in air-to-ground and air-to-air scenarios [23].

2.2. *OWTNs (Optical Wireless Terrestrial Networks)*

OWTNs, as known as outdoor FSO networks, establish a point-to-point and LOS optical wireless connection between two transceivers through outdoor atmospheric turbulence channels [10,11,15,18]. Due to the LOS requirement, the distance of light propagation through free atmospheric space is from hundreds of meters up to tens of kilometers. This telecommunication paradigm has great potential for wireless communications and is becoming an important means for broadband internet access. Some application scenarios are presented below.

- OWTNs are used to bridge existing high-data-rate networks, especially when they are geographically separated. For instance, FSO links for ship-to-ship, building-to-building, or community-to-community communications can be established without ditching and laying optical fibers. Mobile terminals are also easily supported.
- OWTNs are effective solutions for the “last-mile” or “first-mile” problems [10]. Even though optical fiber cables have been widely used, there are still many end-users who do not have their own fiber connection to the Fiber to the Home (FTTH) service. OWTN provides a high bandwidth connection over a large distance for remote end-users (e.g., residents in rural areas).
- OWTNs are integrated with wireless radio networks to mitigate the capacity and scalability limitations of Radio Frequency (RF) channels [24–27]. For example, the throughput and fairness of existing wireless mesh networks are seriously limited, especially when the hop-count is large [6,9]. With a high-speed OWTN overlayed on top of the wireless mesh networks, this scalability problem is easily overcome [28].

Service providers and network architects, however, should take into consideration how to handle link-quality deterioration caused by atmospheric loss such as absorption, scattering, and refraction in clear weather, as well as in bad weather conditions, to maintain reliable connectivity and support the required level of QoS to FSO network users. Many practical solutions have been proposed to adapt to the changing atmospheric conditions, such as diversity techniques [29], hybrid RF/FSO systems [12,30,26], multipath routing algorithms [21], and autonomous topology (re)configurations [31,32]. We will discuss these techniques in more detail later in this survey.

Several FSO transceivers for commercial and military purposes have been developed [33,18,19]. They support transmission distances from hundreds of meters to a few kilometers with data rates ranging from hundreds of Mbps to multiple Gbps. To date, most transceivers have been developed for stationary terminals and links are aligned by manual configurations. There have been some researchers who are investigating the more challenging scenarios of mobile environments and autonomous topology management [18,31–33].

2.3. OWHNs (Optical Wireless Home Networks)

OWHNs, also known as indoor FSO networks, are desirable for wireless broadband communications inside houses and offices. OWHNs are used to construct a LAN comprised of cells, where each cell is one of the divided spaces in the building [11,13,15,34,35]. Usually each cell has a base station to which several terminals are connected with short-range optical wireless links such as infrared and Light Emitting Diode (LED). Unlike radio waves, infrared and LED beams cannot penetrate walls. Each wireless optical cell should be confined to a room and needs to be connected to and integrated with a broadband backbone infrastructure. Usually each cell is free from interference from neighboring cells. As a result, the same beam specifications are reused.

Based on different propagation modes, we further classify the indoor FSO links into two types:

- LOS links and,
- non-LOS links, also known as diffused links.

An LOS link requires a direct path between the sender and receiver. Any unexpected obstacles between the sender and receiver easily break the LOS link. Compared with non-LOS links, LOS links achieve higher capacity because of a better power budget and the absence of multipath propagation effects. A beam-steering mechanism, however, is necessary to support mobile terminals with LOS links. In non-LOS links, a diffused light source is used to disperse a light beam within a room to take advantage of multiple path propagations caused by reflections from all sorts of surfaces in a confined space, such as furniture, walls, ceilings, and floors. As a result, non-LOS links are more robust when encountering obstacles. However, there is a trade-off between network capacity and reliability of connection here. Usually a diffused link supports a lower data rate as compared to LOS links.

Infrared Data Association (IrDA) standards are excellent examples of indoor LOS links. IrDA was founded in 1993 to design wireless point-to-point optical links using an infrared medium [4,36]. Currently, IrDA has become one of the popular standards for short-range wireless networks along with Wi-Fi [37] and Bluetooth [38]. Shipments of IrDA transceivers in 2001 were 100 million units and increased to over 300 million units in 2007. Compared with Wi-Fi and Bluetooth, IrDA transceivers are competitive since they are economical. The cost of a typical IrDA component is about $2 USD while Wi-Fi and Bluetooth components cost around $20 USD and $4 USD, respectively. To establish a connection, the typical IrDA technology requires that both transceivers be located within 30 degrees of each other and that a one meter cone be centered around the line of direct path. IrDA links support data rates varying from several kbps to tens of Mbps. IrDA Very Fast Infrared (VFIR), for example, supports a data rate of 16 Mbps. IrDA IrSimple is a new high-speed-infrared communications protocol designed for mobile devices. It aims at delivering 100 Mbps data rates – some 25 times the data rates of today's IrDA interfaces [36]. In December 2007, Gigabyte Infrared Communications (Giga-IR) was proposed to meet the demand for high bandwidth. The main objective was to develop a protocol for a one Gbps data rate. At the official website of IrDA [36], there is a demonstration of 1 Gbps communication by opto-wireless technology.

Two promising solutions for diffused OWHNs have been proposed, namely, Multi-Spot Diffusing (MSD) [34,39] and white LED lights [35]. Both diffused OWHNs support high speed data transmission over hundreds of Mbps. In an MSD system, the multibeam transmitter is located on the floor and projects multiple beams onto the surface of the room ceiling, while an angle diversity receiver reads diffusing spots. A holographic optical diffuser generates multiple beams to be uniformly distributed to diffusing spots on a ceiling. The key factors to designing MSD architecture are (i) how to configure the shape of multiple beams on the entire surface and (ii) how to increase SNR (Signal-to-Noise Ratio) for each spot. White LED was proposed as the alternative solution; it is considered to be a future commercial lighting appliance with the potential for a massive amount of production. White LED has many beneficial properties such as low-power consumption, high brightness, and little shadowing, and is highly suitable for indoor wireless networks. Furthermore, all electric equipment in the house and office are connected by power lines; each cell using white LED wireless networks can be integrated with Power Line Communications (PLC) [40]. Thus, additional backbone infrastructure for the indoor cells will not be required.

OWHNs provide an effective solution to the proliferation of communication devices and services in office and home networks. OWHNs provide sufficient data rates and channel capacity at a low cost and are thus strong candidates for future home networks. However, it is challenging to provide seamless roaming service to portable equipment, since light mediums usually cannot penetrate cell boundaries.

3. Design factors

In this section, we will discuss critical factors in designing FSO networks. These factors have an influence on the performance of FSO networks and point to the direction of required technology development, algorithms, and protocols.

3.1. FSO channel characterization

FSO uses an unguided beam that propagates through free space as the transmission medium. Such a light, free space channel should be analyzed and characterized. The typical FSO channel conditions fluctuate and deteriorate due to atmospheric turbulence. Indeed, atmospheric turbulence has been one of the main clogging factors of practical deployment. Atmospheric impairment and disturbance degrades FSO channel performance and makes it hard to achieve constant availability and reliability. It is shown in [19] that if a deep fade lasts for $\sim 1 - 100\mu s$ on the multiple Gbps optical channel, up to 10^9 consecutive bits might be lost. The refractive index structure parameter, typically denoted as ${C_n}^2$, represents the strength of the atmospheric turbulence, which has a strong impact on channel fading [41,42,19].

There are many atmospheric turbulence factors such as weather phenomena and scintillation by pressure, humidity, and temperature that affect FSO link quality. When weather conditions are severe, the performance of a free space link will be significantly hampered. However, it is found that channel availability can be achieved with high probability even under severe weather conditions. According to [15], atmospheric attenuation is constantly low, over 99% as measured in three major U.K. cities. When a sufficient power budget is applied, an FSO link availability of up to 99.5% is achievable.

Scintillation, the temporary spatial variation of light intensity, degrades the performance of FSO links even in clear weather. In particular, the variations in temperature dominate the refractive index structure parameter. According to [42], the scintillation effects induced by pressure and humidity are also relatively small, but the effects of temperature are more significant.

The low channel quality problem usually occurs in satellite-to-terrestrial and inter-terrestrial connections, since they are mostly caused by air turbulence. In order to further understand channel conditions, various statistical channel models were proposed in the literature, such as log-normal, *K*-, lognormal-Rician, and Gamma-Gamma distributions [43]. However, the inter-satellite links and OWHNs are usually free from atmospheric influences since the inter-satellite optical beams propagate through the vacuum of space and the distance of OWHN links is negligibly short.

3.2. Link availability and reliability models

The availability and reliability of wireless optical links are essential factors for FSO networks. If the wireless optical links suffer from low availability and reliability, the transmissions will be interrupted and the overall performance of the FSO network will be degraded. There are several sources that deteriorate FSO link quality. In OWTNs, atmospheric turbulence is the main cause of link performance degradation. The narrow beam property of an FSO link is another cause of weak link connectivity. A typical optical beam propagates with a narrow divergence of a few mrad, and the Field of View (FOV) at the receiver is also small [18,33]. Due to these small angles, link loss or inaccurate alignment happens. Thus, Precise pointing, Acquisition, and Tracking (PAT) techniques are indispensable. In the case of mobile platforms such as satellites and airplanes, PAT techniques become more challenging. In addition, optical beams cannot penetrate non-transparent bodies, so if there is any stationary obstacle on the LOS path between two FSO transceivers, it would be impossible to form a link. Even though a wireless optical link exists, it suffers from temporary outages caused by moving objects like birds or snow.

To achieve high availability and reliability, a straightforward approach is to place FSO devices where there is less probability of disturbance by objects and where the weather conditions are better on average. However, there are still opportunities to achieve higher availability and reliability of FSO links by considering and addressing one or more of the sources that affect them. Viable approaches to keep strengthening the availability and reliability of FSO channels have been proposed in the literature. These include autonomous PAT mechanisms [44,33,32], diversity techniques [29,45], hybrid RF/FSO systems [12,30], among others.

3.3. Automation

There are trade-offs when operating FSO links between manually or by automation in order to establish/maintain link connections. The degree of automatic operation depends on the specific application. If the FSO link is deployed in an area with high reliability and does not need to be changed in direction for a long period of time, it is possible to use manual operation with simple tracking mechanisms to save on costs. However, OWSNs, for example, require a high level of automation for the purpose of topology control, since it is impossible to manipulate the direction once satellites have been launched. If FSO transceivers operate autonomously, self-configuration and self-healing algorithms should be developed and incorporated into the system [31,32].

3.4. Network topology design

Though some FSO networking problems have been studied, topology design and optimization have not been investigated sufficiently to this point. Much of the existing research has been confined to exploring only issues involving the physical layer. However, recent experimental successes and technological improvements have enabled researchers to address FSO networking problems. The typical problem in network topology design is what kind of topology should be established, for a given traffic demand and cost constraints. Topology design and optimization depend on the specific design objective. Recently, several types of topologies have been studied. In [31,32], Milner, et al. proposed the bottom-up minimum spanning tree algorithm in order to design initial network topology. The authors also propose congestion minimization heuristics to maintain a flexible topology according to the traffic matrix. Gurumohan and Hui proposed MDT (Modified Delaunary Triangulation) and CN (Closest Neighbor) algorithms to establish a topology for FSO networks aiming for strong connectivity and short network diameter [46].

Topology can be designed for radio channels too. In [30,19,17], researchers explored the future of integrated satellite and terrestrial networks including FSO communications. Similarly, Hranilovic, et al., in [24,25] investigated where to place a minimum number of FSO links in order to maximize the capacity of a wireless mesh network and maximize the number of active links under RF interference constraints.

3.5. Quality of Service (QoS) provisioning

The broadband serviceability of FSO networks is one of its promising advantages due to a very high frequency band. FSO networks will surpass radio wireless networks in this capacity since FSO links pose no limitations on data rate [34]. According to [10], a 1.55 μm laser operating at a 200 THz frequency provides almost 200,000 times more capacity than a 2 GHz microwave link. The FSO links provide a competitive solution to the “last-mile” problem [10], increasing the capacity of existing wireless networks [25], and constituting an important component for the next generation of broadband wireless communication networks [19,31]. However, the capacity of FSO links is limited by transceiver performance [34] and eye safety constraints [11], even though data rates of multiple Gbps can be achieved. How much capacity is achieved is actually determined by the aggregate of individual traffic flows passing through the FSO link.

In addition to the broadband demand, various QoS requirements, such as end-to-end transmission delay, jitter, packet loss rate, and fairness, should be taken into consideration when designing networking algorithms and protocols in FSO networks. For example, the end-to-end delay is an important factor due to the long round trip distance in OWSNs [19], while fairness may be a concern for an OWHN in a room serving multiple devices. The current congestion control mechanism in the Transmission Control Protocol (TCP) may not work well in an FSO network and could lead to poor throughput performance, and thus more flexible protocols should be developed for FSO networks.

3.6. FSO link cost

An FSO link is a point-to-point connection. Thus, each link needs two transceivers at both ends. It means that the number of required devices is proportional to the number of required connections in the FSO network, so the cost of the FSO device is an important design factor in terms of network deployment and operation. In OWHNs, a typical IrDA component costs just about $2 USD, which is relatively inexpensive. However, the purchase and installation cost of OWTNs is estimated to range from $10,000 USD to $25,000 USD for medium and long-distance links as in 2003 [47]. Hence, it is necessary to further develop transmitters and receivers in consideration of production and deployment cost. Chan in [19] discussed high system costs and proposed to develop photon-counting receivers and a coherent system for vacuum and air turbulence channels in order to reduce system costs.

3.7. Eye safety

High-power beams suppress atmospheric disturbance and make it possible to further meet required data rates under severe weather conditions. Although FSO transmissions usually do not cause mutual interference (unless pointing to each other), laser sources beyond a certain power threshold are harmful to the human body, in particular, the eyes. Thus, it is important to enforce a limitation on laser-emission power in optical wireless networks.

Laser safety standards have been established, such as ANSI Z136.1

and IEC 60825-1 [11]. According to IEC 60825-1, the objective is to protect the human body from excessive laser radiation with wavelength ranging from 180 nm to 1 mm, by classifying lasers and laser products based on their degree of hazard. The optical beams in Class 1 and 2 are considered completely safe except when direct and lengthy exposure is involved. The Class 3 beams achieve a good power budget, but are not recommended to come in contact with the human body. Interested readers are referred to [11,15] for detailed information. The performance of FSO systems are degraded by the safety regulations, i.e., the constraints on transmit power [11]. Operating low power sources requires the availability of highly sensitive receivers, which may suffer from more interference from the environment.

4. Research challenges

FSO networks have enormous potential for high capacity of over Gbps per link. The transmission is normally conducted using an LOS propagation with a directional narrow beam over a long distance. FSO channels are deployable on a wide range of areas from home to terrestrial, and to satellite. Those unique properties have sparked a large amount of research. However, research on fully harvesting the potential of FSO networks are still in its infant stage, and many important and challenging problems still need to be solved. We discuss research challenges, existing solutions and open problems in this section. Our discussions are also summarized in Table 2.

4.1. Channel modeling

For several decades, there have been many research studies performed on developing mathematical models for optical wireless channels [48], to quantify the impact of atmospheric turbulence on link performance. It is meaningful to fully understand channel fading properties of optical signals in the free space medium. As a consequence, various statistic channel models have been proposed, such as log-normal, *K*-, lognormal-Rician, and Gamma-Gamma distributions based models [43]. Such statistical models provide insights on understanding the FSO channel, which in turn lead to ways to improve such channels.

As a representative example, we review the log-normal channel model to show how link reliability is strongly affected by atmospheric turbulence. Atmospheric turbulence is represented as the refractive index structure parameter, denoted as $C_n{}^2$. According to [41], the marginal distribution of light intensity fading induced by atmospheric turbulence is statistically modeled as

$$f_I(I) = \frac{1}{2\sigma_X I}\frac{1}{\sqrt{2\pi}}\exp\left\{-\frac{(\ln(I)-\ln(I_0))^2}{8\sigma_X^2}\right\} \tag{1}$$

where $\sigma_X{}^2$ is the variance of the log-amplitude fluctuation X of plane or spherical waves and I_0 is the received average intensity without turbulence. The mean is $e^{\ln(I_0)+2\sigma_X^2}$ and the variance is $(e^{4\sigma_X^2}-1)e^{2\ln(I_0)+4\sigma_X^2}$. The standard deviation of the log-amplitude fluctuation $\sigma_X{}^2$ is derived as

$$\sigma_X^2 = 0.30545\left(\frac{2\pi}{\lambda}\right)^{7/6} C_n^2(L) z^{11/6} \approx \frac{\sigma_R^2}{4} \tag{2}$$

where $\frac{2\pi}{\lambda}$ is the optical wave number with wavelength λ, $C_n^2(L)$ is the index of refraction structure parameter with constant altitude L, z is the transmission distance, and $\sigma_R{}^2$ is the Rytov variance, which is defined as

$$\sigma_R^2 = 1.23 C_n^2(L)\left(\frac{2\pi}{\lambda}\right)^{7/6} z^{11/6}. \tag{3}$$

According to [41], for atmospheric channels near the ground (i.e., $L < 18.5$ m), $C_n{}^2$ ranges from $10^{-13}\,\mathrm{m}^{-2/3}$ to $10^{-17}\,\mathrm{m}^{-2/3}$ for strong and weak atmospheric turbulence, respectively. The common average is $10^{-15}\,\mathrm{m}^{-2/3}$. Fig. 2 illustrates the relationship between the standard deviation of the log-amplitude fluctuation (i.e., σ_X) and the index of the refraction structure parameter (i.e., C_n^2). In the case when FSO links suffer from strong atmospheric turbulence through the propagation path, the intensity of the received light signal will greatly fluctuate.

The link reliability (Γ) is derived from the probability density functions for log-normal distribution as

$$\begin{aligned}\Gamma = P(I \ge I_{th}) &= \int_{I_{th}}^{\infty} \frac{1}{2\sigma_X I}\frac{1}{\sqrt{2\pi}}\exp\left\{-\frac{(\ln(I)-\ln(I_0))^2}{8\sigma_X^2}\right\}dI \\ &= \frac{1}{2} - \frac{1}{2}\mathrm{erf}\left(\frac{\ln(I_{th})-\ln(I_0)}{2\sigma_X\sqrt{2}}\right)\end{aligned} \tag{4}$$

where I_{th} is the threshold of received signal intensity [28]. Equation (4) shows that, for a fixed ratio of I_{th}/I_0, the link reliability is determined by the standard deviation of the log-amplitude fluctuation (i.e., σ_X), which

Table 2
Challenges and possible solutions in FSO Networks.

	Challenges	Viable Solutions
FSO link problems	Channel randomness	- Statistical channel modeling with various fading factors
	PAT	- Coarse- and fine-pointing system - Omnidirectional control channel - Autonomous PAT system
	Outage/Fading	- Spatial diversity technique - RF/FSO hybrid architecture - Advanced components
	Diffusive optical link	- MSD - White LED
FSO network problems	Adaptive topology control	-Self-configuration algorithm - Self-healing algorithm - Autonomous PAT system - Network monitoring
	Network robustness	- Mesh connectivity - Multipath routing protocol - Autonomous topology reconfiguration
	Network congestion	- Dynamic rate allocation - Autonomous topology reconfiguration
	TCP performance	- Efficient TCP variant - Shortest path routing - Minimum hop routing

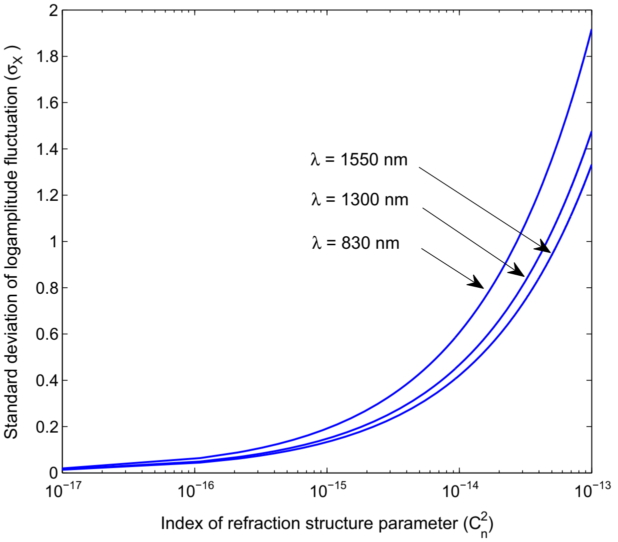

Fig. 2. Standard deviation of log-amplitude fluctuation (σ_X) versus index of refraction structure parameter ($C_n{}^2$). The wavelengths are 830 nm, 1300 nm, and 1550 nm, respectively. The propagation distance is 2 km.

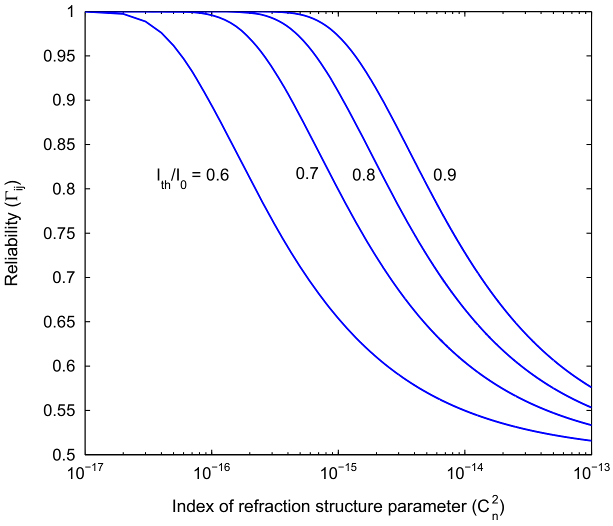

Fig. 3. FSO link reliability (Γ_{ij}) versus index of refraction structure parameter ($C_n{}^2$). The wavelength is 1550 nm on the 2 km path. The ratios of I_{th}/I_0 are 0.6, 0.7, 0.8, and 0.9, respectively.

is strongly influenced by weather conditions. Indeed, Fig. 3 shows that the link reliability is diminished as weather condition becomes severe (i.e., as $C_n{}^2$ is increased).

Open Research Issues. Statistical modeling of intensity fluctuation of received light signal has been a challenging research issue for a long time, but it is still an open problem due to there being a broad spectrum of applications from home, terrestrial, and satellite. Furthermore, there are many factors impairing link performance. For example, a channel model combining the effects of atmospheric turbulence and pointing errors has been proposed [49]. It would also be desirable to take into account mobile or static obstacles in FSO channel modeling.

4.2. PAT (Pointing, Acquisition, and Tracking)

Pointing, Acquisition, and Tracking (PAT) schemes have been essential when deploying and operating optical wireless links. Typically, FSO transceivers have a broadband and point-to-point directional link in a beeline between the sender and receiver. Transmitters shoot out narrow beams and the divergence of the beams is less than a few *mrad*. Receivers have a small angle degrees for the FOV. This extremely narrow beam property results in optical space links having less interference and are more energy-efficient, and more secure with LPI/LPD. On the other hand, these properties make the FSO link difficult to establish between two endpoints. To maintain connectivity between two endpoints, both sides need to point at each other with a precise LOS direction during transmission. According to [18], OWSNs require 1–10 μrad pointing accuracy for supporting a data rate of 10 Gbps. As the distance between the two endpoints gets larger, it becomes more challenging to design effective PAT techniques. In OWSNs, the propagation distance between two satellites can be up to 84,000 km, and it becomes a great challenge to design precise PAT techniques for maintaining high data rates with such large distances.

The pointing mechanism starts with finding out where potential nodes exist for establishing a link in the three dimensional free space before beginning the connection procedure. This is similar to the neighbor discover procedure in millimeter wave (mmWave) networks [50,51]. Since there may be many connection options when multiple nodes are within range of each other, FSO nodes need to coordinate themselves with respect to to which node to point. That is, there is an inherent network design problem associated with the pointing mechanism [28,52]. Even for stationary nodes, e.g., where FSO transceivers are mounted on top of buildings or geostationary satellites, it is non-trivial that an initial connection be established between two transceivers due to the narrow beam property. Furthermore, coordinating the two endpoints, or synchronization, during operation is also a challenging task, especially for mobile users. FSO network nodes, e.g., OWSN or OWTN nodes, are normally far away from each other. It is also important to synchronize the pointing procedure of the two endpoints to establish an FSO link, even though the location of neighboring nodes are known.

Several promising approaches supported by specific hardware design have been proposed even though PAT problems still remain as an open problem. In order to recognize the existence of each other, a coarse-pointing system having a beacon signal with a wide divergence angle is presented [33,44], or a coarse-sensing system is an alternative option by using a wide FOV at the receiver. In [32], an omnidirectional beacon mounted on gimbals is proposed as a prototype in order to exchange the location information. Once the coarse-seeking procedure is completed, a fine-pointing procedure follows. In [53], Shim, Milner, and Davis demonstrate a precise pointing technique with their experiment involving an outdoor testbed, utilizing real-time Kinematic GPS coordinates.

The *acquisition* mechanism is related to signal modulation and detection techniques. Since it is possible that multiple optical beams can be intercepted by a receiver aperture, the receiver should then decide which signal is the desired one that needs to be decoded. For example, a binary morphological technique in [32] is applied to distinguish between different optical signals. Regarding the aspect of physical architecture, the size of the receiver aperture needs to be adjusted according to the divergence angle of the emitted laser beam and the distance, in order to maximize the efficiency of the power budget. In [49], Farid and Hranilovic develop statistical models for outage probability and achievable rates while taking into account beam width, pointing error, and detector size.

The *tracking* mechanism is also used to address the problem induced by the narrow-beam property. Signal tracking mechanisms need to be under consideration even between stationary transceivers, since FSO links need very high pointing accuracy, and misalignment of optical beams leads to a reduction of the available capacity and increase of outage probability. When node mobility increases, more delicate hardware and protocols are needed. If the receiver fails in keeping track of the current connection, it should go back to the coarse-seeking mechanism to recapture the transmitter beam. For running a tracking mode in OWSNs, a centroid algorithm utilizing windowing techniques is applied in [44] in order to evaluate the impact of the misaligned angle of the received beam. In [54,55], the performance of alignment and tracking corresponding to terrestrial FSO stations is investigated.

Open Research Issues. To the best of our knowledge, PAT problems have not been completely solved in spite of its significance, long investigations, and promising approaches. We believe the following problems need more investigation.

- Hardware architecture for dynamic PAT: even though there has been active research on PAT problems, it has not progressed enough to be sufficiently flexible on various platforms. Some researchers are interested in automated PAT mechanisms, but the subject has not been fully explored. For effective PAT, an integrated and flexible solution is needed.
- Synchronization: a time synchronized PAT process is another critical issue. To make an initial connection, both transceivers need to point at each other simultaneously. In this case, a specific method is needed that will allow transceivers to exchange control information, such as location, mobility, and time to meet in space. If both platforms are in motion, the synchronized alignment of transceivers for tracking is also required.

4.3. Advanced hardware design

Link reliability is an important requirement for FSO networks.

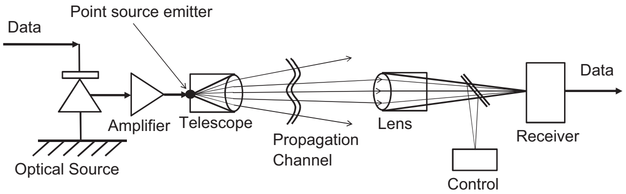

Fig. 4. An example architecture of outdoor FSO transmitter and receiver design (adapted from [56]).

Indeed, the FSO networks cannot be stabilized and viable unless transmitters and receivers maintain reliable wireless optical links during operation. Fig. 4 (adapted from [56]) shows an example of outdoor FSO transmitter and receiver design. The transmitter converts electrical signals into optical power and emits light beams into the atmosphere with a minimum divergence, and the receiver transforms the received optical signal into a photocurrent. As shown in Fig. 4, the divergence angle of the transmitter, the aperture size of the receiver, and atmospheric impairment affect the received power. The main concern has been the turbulent air conditions, so advanced techniques that mitigate their effects are desirable.

There have been several approaches used with regard to advanced transmitter and receiver techniques meant to increase the reliability and stability of FSO links. Two examples are the Multiple Input Multiple Output (MIMO) systems and a hybrid of radio frequency and optical beam [12,30]. Adopting diffusive wireless optical systems like MSD [34,39] and white LED lights [35] also increase link reliability, but sacrifice performance and may not be proper for outdoor FSO networks.

Spatial diversity techniques such as MIMO systems have already been proposed and widely used for radio wireless systems like LTE [5,57–60]. The typical MIMO design uses an array of antenna components at the transmitters and/or receivers in order to increase capacity and overcome channel fading. The authors in [29,45] show that this technique is also useful in wireless optical networks, and it is effective for turbulent atmospheric channels. Lee and Chan in [45] show that a MIMO system significantly reduces the probability of outage and increase power gain than a single transmitter and receiver set. Recent work shows that a MIMO FSO system achieves significant diversity gains in the presence of atmospheric fading by deploying multiple transmit or receiver apertures [61,62].

However, the FSO MIMO system performance is limited by its thermal noise-limited receiver, and thus Avalanche Photodiodes (APDs) [63] are commonly used in FSO systems. Adaptive transmission technology in these systems, used to mitigate weather turbulence, was recently studied. The conventional radio wireless adaptive modulation and coding method can be applied to FSO systems [64]. However, to better enhance system performance, these conventional methods should be evaluated and studied by including consideration of optical channel features. Karimi and Uysal in [65] design transmission algorithms with consideration of the number of bits carried per chip time (BpC) of an optical wireless link, in which Intensity Modulation/Direct Detection (IM/DD) with M-ary Pulse Position Modulation (*m*-PPM) is employed. Additionally, varying wavelengths became feasible as the Quantum Cascade Lasers (QCL) technology matured [66]. It is now possible to use variable wavelengths to combat the effects of atmospheric impairments.

The hybrid RF/FSO architecture has been considered as one of several practical techniques since both technologies make up for the other's limitations. The radio frequency penetrates, diffracts, reflects, and scatters on obstacles and omnidirectional propagation is widely practiced. Thus, it is not so difficult to maintain connections with neighbors. However, wireless radio networks have limitations in capacity and scalability. To achieve better performance, more spectrum should be used, but at a great cost since radio spectrum is not free. Furthermore, it needs expensive and complex components. In contrast, an optical beam is license-free to use and supports high data rate transmissions. The small divergence angle of its light source, however, makes it hard to establish and maintain a connection. To make matters worse, the performance of a wireless optical channel deteriorates or is made unsatisfactory due to severe atmospheric conditions, inaccurate alignment, various kinds of obstacles, and so forth. According to [30], optical beams are highly susceptible to dense fog, mist, snow, and dust particles, but are relatively less impacted by rain while radio frequency signals, especially at over 10 GHz bands, suffer from significant deterioration caused by rain (but less affected by snow).

Several scenarios have been studied in an operating hybrid system of RF and FSO. A typical example is that of both channels working in parallel [30,12,19]. While FSO links support high bit rates, radio channels provide additional capacity to support the current traffic load. In the case of a complete outage of optical links, all the traffic will be carried on radio channels temporarily. Meanwhile, Hranilovic et al. explore upgrading the capacity and mitigating the radio interference of existing wireless mesh networks by inserting FSO links selectively at strategic locations [24,25]. In [67], hybrid FSO/RF systems were integrated at the macro-cellular tier to enable high-capacity and power-efficient wireless backhauling. Desai and Milner in [31] suggest that radio frequency be used for the purpose of keeping FSO links connected. It is also possible that a radio channel can be used as a control channel in the process of PAT.

Due to the complementary nature of radio and FSO communications, both in capacity and coverage, the combined use of both technologies for data transmission is advantageous over a single media [68]. There are many ways to explore the potential of FSO and ways to incorporate both FSO and RF in wireless networks. The main challenge of implementing hybrid FSO/RF networks is the dynamic, autonomous reconfiguration both in hardware and software needed in order to maximize the availability and capacity for tactical operations.

Open Research Issues. There have been many research studies on improving the FSO architecture and advanced hardware design, and this is still an active research area.

- Advanced techniques and hardware design: using advanced hardware techniques for improved reliability and reduced cost, still needs to be investigated. For example, dynamic adjustment of beam divergence at the transmitter and FOV of the receiver according to distance and turbulent channel conditions increases power efficiency. Another example is to incorporate Wavelength-Division Multiplexing (WDM) to significantly increase the capacity of FSO links [69,70].
- Hybrid RF/FSO systems: a hybrid system of RF and FSO links could be fully explored. In particular, it is still challenging to maximize reliability and bandwidth utilization under turbulent channel conditions [12,30]. Solutions could include techniques across multiple layers, including dynamic rate allocation, routing, and topology monitoring.

4.4. FSO networking

Most of the work on FSO has been focused on the PHY and hardware design; the FSO networking issues have not attracted comparable attention in the research community. There has been some progressive growth in this aspect [10,19]. Link reliability has been enhanced and autonomous PAT schemes were proposed [32]. As a result, various types of FSO networks were proposed and corresponding challenges have arisen. FSO networks have distinct properties, as compared to radio wireless networks, which should be considered when addressing FSO networking problems. For instance,

- Unlike in radio wireless networks, interference is a much less an issue in FSO networks. Therefore, wireless optical channels are

aggressively spatially reused. In addition, a non-planar graph is feasible to model an FSO network, to which many advanced graph thoery based techniques can be developed and applied [28,51,71].
- The number of possible neighbors is determined not only by the number of candidate neighbors, but also by the number of FSO transceivers available at each FSO node. This is a new constraint for FSO network topology design.
- The goal of topology design can be accomplished by constructing the physical network topology. However, unlike a wireline network, the links in an FSO network are easily redirected based on need during operation, for example, to accommodate new traffic demand, or to get around a failed/blocked FSO link.

For topology design, only a small amount of research has been performed that takes into account the features of FSO networks. Solutions should vary, based on the objective of topology design. In [32], an approximation algorithm is proposed to make FSO nodes operate in a distributed fashion until a degree-bounded spanning tree is configured. Another goal is to reduce time complexity, namely the time it takes to form the FSO topology. The work in [31] is motivated by the fact that dynamic alignment of FSO links reduces network congestion. For this purpose, congestion minimization heuristics are proposed. In [46], the authors propose two centralized algorithms. The first algoirhtm constructs a backbone network by Delaunay triangulation, while the second algorithm constructs a degree constrained minimum weight spanning tree. The goal is to build a topology with strong connectivity and a short diameter. In order to measure network robustness, various metrics of network connectivity can be used, such as k-edge/vertex connectivity, bisection connectivity, and algebraic connectivity [28,52,71].

Practically speaking, the physical topology of an FSO network is expected to be the (quasi-)mesh topology, which is more robust to link failures [46]. Thus, each node needs to be equipped with a few FSO transceivers (i.e., a node degree higher than one). Some FSO architectures include radio channels for backup or assistance (e.g., providing a control channel), since FSO links can be interrupted or have their performance severely deteriorated [30]. Therefore, adaptive routing algorithms for multiple channels and heterogeneous transmission media need to be introduced in the hybrid design context.

The cooperative diversity technique [72–74] is also a cost-effective candidate for enhancing FSO system performance. If the FSO base station transmits cooperatively with another FSO base station whose surrounding weather condition is better, the channel degradation can be greatly mitigated. Relay-assisted FSO communication has been studied in [72-75]. Both serial and parallel relaying coupled with amplify-and-forward and decode-and-forward cooperation modes are considered in [75]. The authors adopt multiple-relay communication to shorten the distance between FSO bases stations and reduce the hop counts, resulting in considerable performance improvements. The work in [75] was extended in [74] and, further, the authors provide an interesting diversity gain analysis. The authors in [72,73] developed effective algorithms for joint relay selection and power allocation in cooperative free space optical networks. In a recent work [76], a one-relay cooperative diversity scheme was proposed to combat turbulence-induced fading, and cooperative diversity is analyzed for non-coherent FSO communications. Numerical results demonstrate considerable performance gains over non-cooperative FSO networks. Abou-Rjeily and Haddad in [77] study cooperative FSO systems with multiple relays. An optimal power allocation strategy to enhance the diversity order and minimize the error probability is proposed. The authors discovered that the solution is to transmit with the entire power along the strongest link between the source and destination. These prior works on cooperative FSO networks focused on physical layer aspects, and networking problems in cooperative FSO networks should be addressed in order to fully exploit the potential of the cooperative diversity technique in FSO networks.

At the same time, it is necessary to further consider how to guarantee the QoS requirements of FSO network users. The broadband serviceability of each FSO link should be preserved even in the case of a fully connected topology. The end-to-end transmission delay, jitter, packet loss rate, and fairness should be considered. Effective networking algorithms and protocols can provide guarantees on these QoS requirements, but such solutions require interactions with protocols in other layers [19].

Open Research Issues. the following FSO networking related problems can be further studied, for which effective algorithms and protocols need to be developed.

- Integrated topology design: the possibility of global operation has been introduced [17,30], but it is still under investigation. In addition, topology design for an RF/FSO hybrid network is still an interesting problem.
- Topology design with QoS guarantees: it is desirable to provide QoS guarantees to FSO network users. A unique feature that can be exploited in FSO networks is that, the network topology can be dynamically adapted for this purpose. The topology of OWSNs should consider a long round trip time for mitigating performance inefficiency. In [31], the authors indicated that the topology design of three and higher degree networks remains an open problem for further research, where the objective is to minimize congestion.
- Distributed topology design: for maintenance of a wide range of FSO networks, centralized design algorithms have great limitations in practice [78]. Thus, decentralized approaches in topology design are necessary [79,80,32].
- Dynamic rate allocation: in the case where there are multiple FSO paths to which traffic packets are assigned, dynamic rate allocation can be challenging since the temporary performance of each path changes according to atmospheric turbulence. It is necessary to make traffic flow more flexible so that it can accommodate channel conditions and avoid congestion [71].

4.5. Transport layer issues

To date, successful transport protocols which would match the distinct features of FSO networks have not been proposed yet [19]. Furthermore, there is no active research on transport layer problems in the context of FSO networks. Therefore, further investigation is necessary. The authors in [81] indicate that FSO links need different communication protocols since the behavior of optical wireless channels with respect to transmission errors are distinct.

In [19,17,81], it has been shown that the current congestion control scheme in TCP causes poor throughput in FSO networks. Especially in OWSNs, the transmission distance between satellite links is immense and, therefore, the long end-to-end transmission delays should be considered in congestion control. In addition, FSO networks support high data rate transmissions with temporary outages. These properties cause poor efficiency in typical transport layer protocols (i.e., TCP). When there are outages, a huge amount of packets could be lost and the congestion control mechanism goes to slow start mode. Note that TCP does not distinguish packet losses due to link outage and buffer flow, and any packet loss indicates congestion to TCP. It will take 10–100's of long round trips to recover the full system rate after every outage. In [19], it is shown that current TCP's throughput is less than 10% even though advanced hardware techniques are utilized. Under such circumstances, end users cannot take advantage of the broadband services either. Hence, a TCP variant (or enhancement), which is resistant to long transmission delay and occasional outages during long-distance transmissions, is needed.

Open Research Issues. Research on the transport layer problems is still in the early phase. For the problem of long end-to-end transmission delay, an efficient TCP variant has not been successfully developed yet. Other distinct features of FSO networks, e.g., high bandwidth through very long propagation distance, temporary outages, and large capacity variations, cause challenging issues with respect to transport layer protocol design.

5. Conclusion

In this paper, we presented a comprehensive survey of FSO communications and networks, ranging from home, to terrestrial, and to satellite optical wireless networks, to provide the architecture, big picture, and state-of-the-art of this important wireless technology. We also discussed important design factors in FSO networks and reviewed existing solutions proposed in the literature. Although FSO communications have been studied for years, FSO networking is still in its infant stage. We provided detailed discussions of research challenges and open problems in FSO networks, which require considerable research effort for practical solutions.

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