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Free Space Optical Networks: A Survey

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Abstract: *Optical wireless networks, also known as Free Space Optical (FSO) networks have emerged as a promising solution for future high speed networks, and for broadband wireless communications. The range of the potential application of FSO networks is very vast, from home to satellite. FSO is in very much demand because of their ability to efficiently manage network resources, and it provides better spectrum utilization to fulfill with the rapid change in traffic behavior and the huge growth in bandwidth demand. However, these FSO networks have not been much popularized because of insufficient reliability and availability. Researchers have focused on the problems in the physical layer to get benefit of the properties of wireless optical channels. And also, the recent technological developments with successful results makes it possible to explore the advantages of the large bandwidth. The problems of network and upper layers in optical wireless networks attracted the attention of researchers. In this paper, we present a study on global FSO networks and will discuss what kinds of challenges exist in this area.*

Keywords-*Free Space Optical, wireless communications, spectrum, bandwidth demand, network*

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I. Introduction

Free Space Optical (FSO) networks, or optical wireless networks, are wireless telecommunication networks that deliver optical data signals at high bit rates using free space as a transmission medium. FSO research started in the 1960s. Many countries are funding various FSO projects for developing high-data-rate laser links in space. Although optical wireless communication provide high data rates, but wireless communications have not been powerful so far in spite of a long research. As new progress is made in optics and communication devices, there has been a renewed, increasing interest and demand in carefully studying and improving wireless optical links and following FSO technology for wireless access networks. Recently, experimental results [1] demonstrated the accessibility of FSO communications. The FSO network could become a promising candidate for the next generation and will be used in broadband wireless networks. Researchers at the German Aerospace Center [2] presented FSO data transmissions at 1.72 terabits per second across a distance of 10.45 km. Wireless communications have many advantageous properties that are not found in wired communications, some of them are the lower deployment cost due to the lack of having to dig a channel and lay down cables, easy construction of network topology, flexible maintenance of operating networks, and much more another benefit of wireless communications is that it allows users of mobile devices to use the Internet at any time and at any location where the network is reachable. For example, IEEE 802.11 (Wi-Fi), Bluetooth, and IrDA are considered for short-range wireless data communications [3], while Long-Term Evolution (LTE) is intended for long-range wireless communication for both mobile phones and data terminals purpose [4].

As the number of mobile devices is increasing tremendously, leading to the establishment of omnipresent networks, wireless communication services are now essential to many people, like regular use supply of water and electricity. Therefore, this leads to the vast growth in the volume of data traffic carried on wireless networks. Additionally, various multimedia services which use data sharing, like AOD (Audio on Demand), VOD (Video on Demand), and P2P (Peer-to-Peer) enhances the requirement of higher data rate networks. To meet the huge demand for wireless data capacity, radio-based wireless communications are mostly used, but they have certain limitations on scalability and bandwidth. For example, there are some technical problems in Wireless Local Area Networks (LANs), one of the considerable wireless access technologies, which resist the support of this increasing volume of data networks. wireless LANs suffer from some problems like (i) low end-to-end throughput due to the restriction imposed by raw channel capacity and forwarding load [5],(ii) high overhead of MAC protocols which further decreases the available throughput [6][7], and (iii) fairness issue and also the interruption of flows [5][8]. FSO networks are considered to be a good choice and provide a solution to these issues.

Advantages of FSO networks over radio wireless networks are given below. Detailed comparisons is available in [9-12].

- Optical wireless links provide very high data rates in the range of Gbps,that is used to support broadband data services.
- There is no need to get the license for using the optical spectrum; it is license-free. Therefore, licensing fees can be saved in comparison to other wireless Radio frequency (RF) based technologies.
- Optical beams are protected from electromagnetic interference.
- Optical components consume less power and are less expensive compare to RF signals.
- Due to properties like narrow beam and point-to-point transmission, special optical links have the sensible LPI/LPD (Low Probability of Intercept/Low Probability of Detection) properties.
- Light sources have negligible mutual interference for indoor purpose.

The main problems that disturb the deployment of FSO. The first one is atmospheric disruption which affects the propagation of optical signals, leading to performance degradation regarding various parameters such as SNR (Signal-to-noise Ratio), BER (Bit per Error Rate), outage frequency, and so on. Effects of Weather on the connectivity of FSO networks were analyzed in [13], and it was shown that weather affects strongly the quality of FSO networks. The second problem is regarding the Pointing, Acquisition, and Tracking (PAT) technique, which is extremely necessary for FSO systems because of its propagation pattern through free space. As the FSO transmitter is highly directional, so the FSO systems are many times designed with some divergence to concentrate the optical energy at a receiver. Because of the narrow beam property, exact alignment of the beams is required. For communication to take placeeach “optical transceiver” must be pointed at each other.

Many researchers are focusing on these critical problems, but usually, for the single-hop, commercial transceivers are often used for bridging two remote stations. In some introductory papers, such as [10,14,12,15], it is presented that satisfactory performance of a single link can be achieved by using an advanced PAT technique. These links are becoming reliable and durable so researchers can focus towards the network and upper layers in FSO networks [9,16,17].

In this paper, we present a survey of the design factors, network architecture, and research challenges for Optical wireless networks. Recent research regarding the physical and the network layer is discussed. We also suggest a new vision for practical problems to build reliable networks. There have been many informative review papers on FSO networks, which gives a broad view of FSO networks [14,10,9,18,17]. The objectives of [10,14] are to present the potential advantages, properties, and existing limitations then further it suggests possible applications. Meanwhile, FSOnetworks are emerging as a very convincing option to become a part of the future generation broadband wireless networks. In [9,18,17], the focus is towards the applications of FSO networks and their challenges. However, many challenging issues have raised in FSO links, which needs more attention. FSO networks have an extensive range of, from home to satellite with a network perspective. Our survey covers recent work and will help researchers to find out new networking problems for FSO networks.

The remainder of this paper is organized as follows. We first review FSO network and present a classification of FSO networks in Section 2. We then present various necessary design factors in FSO networks in Section 3. Then, research challenges in FSO networks are discussed in Section 4, including various parameters. Section 5 concludes this paper.

II. Classification Of FSO Networks

Due to their high potential, FSO networks are employed for a broad spectrum of networks. As shown in Fig. 1, FSO networks can be 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 network range and locations of transmitters and receivers. Various FSO subnetworks are combined and operated as a whole for easy operation, as shown in Fig. 1 [19].

2.1 Optical Wireless Satellite Networks (OWSNs)

Satellite Networks are designed to cover large areas of the earth and provide high-bandwidth network access to consumers [20,15,18]. It establishes a global network with optical links since satellites can support any terrestrial residents within Line-of-Sight (LOS) range. Therefore, OWSNs gives high quality services globally even to isolated areas also. OWSNs consist ofvarious types of free-space links such as satellite-to-surface, inter-satellite, satellite-to air optical links. Inter-Satellite Links are designated for routing data through satellites. Generally, suchlinks have very high data rates, so these are used for very long distance communications like inter-continental.

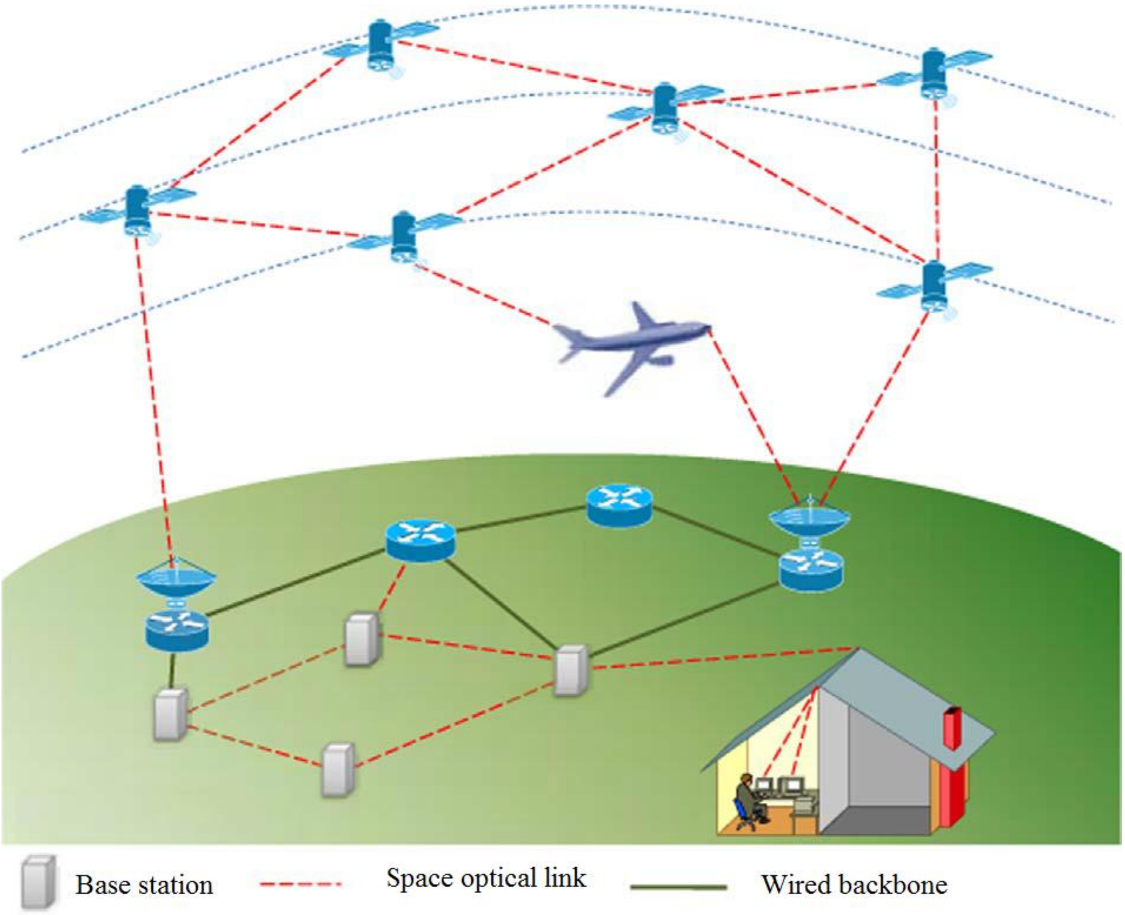

Figure 1: Allocation of connections (a) using FF and (b) using FSF.[19]

Geostationary Earth Orbit (GEO: ∼40,000 km altitude), MediumEarth Orbit (MEO: ∼5,000–15,000 km), and Low Earth Orbit (LEO:∼1,000–2,000 km) satellites, along with FSO links, serve as commerciallyviable backbone nodes as stated in [15]:

- OWSNs are used for over-the-ocean communications as replacement for the current wired internet that is mostly carried through undersea optical fiber systems.
- OWSNs easily overcome the obstacles of long distances do not need undersea cables infrastructure.
- With OWSNs, broadband wireless services can be easily provided for secluded areas even to remotely located mobile users which is hard with traditional network technologies.

Service providers and network architects should consider both technical and economical factors to ensure success. This is because the initial investment in satellite systems is considerable, and then maintenance is impossible once satellites are launched. Therefore, various design factors are critical issues such as link capacity, physical topology, and routing strategy that need to be carefully addressed [21]. There is need of proper efforts made in the investigation and development of reliable and robust satellite-based FSO systems [15]. Military organizations are also taking much interest in developing OWSNs required for strategic and tactical operations.

2.2Optical Wireless Terrestrial Networks (OWTNs)

OWTNs, also called as outdoor FSO networks, uses outdoor atmospheric turbulence channels to establish a point-to-point and LOS optical wireless connection between two transceivers [9,10,14,17]. The distance of light propagation through free space is from hundreds of meters to tens of kilometers because of the LOS requirement. This telecommunication model has the great advantage for wireless communications and is becoming an important aspect for broadband internet access. Some application scenarios are shown below.

- OWTNs are used to build existing high-data-rate networks, especially in the case when they are geographically separated. FSO links can be established without laying optical fibers.

- Mobile terminals are easily supported. OWTNs are important solutions for the problems of "last-mile" or "first-mile" [9]. OWTN provides a high bandwidth connection over a large distance for remote end-users through Fiber to the Home (FTTH) service(e.g., residents in rural areas).
- OWTNs are combined with wireless radio networks to remove the scalability and capacity limitations of Radio Frequency (RF) channels [22,23,24,25]. Such as the throughput and fairness of existing networks are critically limited, especially when the hop-count is large [5,8]. Scalability problem can be eliminated with a high-speed OWTN overlaid on top of the wireless mesh networks [26].

Service providers and network architects, however, should take into consideration how to handle link-quality deterioration caused by the 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 [27], hybrid RF/FSO systems [11,28,24], multipath routing algorithms [21], and autonomous topology (re)configurations [29,30].

2.3 Optical Wireless Home Networks

OWHNs, also known as indoor FSO networks, are desirable forwireless broadband communications inside houses and offices.OWHNs are used to construct a LAN comprised of cells, where eachcell is one of the divided spaces in the building [10,12,14,31,32]. 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 frominterference from neighboring cells. As a result, the same beamspecifications are reused. Based on different propagation modes, further classification of indoor FSO links:

- LOS links and,
- Non-LOS links, or diffused links.

A LOS link requires a direct path between the sender and receiver.Any unexpected obstacles between the sender and receiver easily breakthe LOS link. Compared with non-LOS links, LOS links achieve highercapacity because of a better power budget and the absence of multipathpropagation effects. A beam-steering mechanism, however, is necessaryto support mobile terminals with LOS links. In non-LOS links, adiffused light source is used to disperse a light beam within a room totake advantage of multiple path propagations caused by reflectionsfrom all sorts of surfaces in a confined space, such as furniture, walls,ceilings, and floors. As a result, non-LOS links are more robust whenencountering obstacles. However, there is a trade-off between networkcapacity and reliability of connection here. Usually, a diffused link supports a lower data rate as compared to LOS links. 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.

III. 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 a 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. Atmospheric impairment and disturbance degrades FSO channel performance and makes it hard to achieve constant availability and reliability. It is discussed in [18] that if a deep fade lasts for some micro seconds on the multiple Gbps optical channel, up to 109 consecutive bits might be lost. The refractive index structure parameter, typically denoted as σ_x, represents the strength of the atmospheric turbulence, which has a strong impact on channel fading [33,34,18].

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, theperformance 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 [14]. Inparticular, the variations in temperature dominate the refractive index structure parameter. According to [34], the scintillation effects induced by pressure and humidity are also relatively small, but the effects oftemperature are more significant. The low channel quality problem usually occurs in satellite-to terrestrialand inter-terrestrial connections, since they are mostly caused by air turbulence. 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 [17,35]. 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. Also, 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.

3.3 Automation

There are trade-offs when operating FSO links between manually orby automation toestablish/maintain link connections. Thedegree of automatic operation depends on the specific application. Ifthe FSO link is deployed in an area with high reliability and does notneed to be changed in the direction for a long period, it is possibleto use manual operation with simple tracking mechanisms to save oncosts. However, OWSNs, for example, require a high level of automationfor the topology control, since it is impossible tomanipulate the direction once satellites have been launched. If FSOtransceivers operate autonomously, self-configuration and self-healing algorithms should be developed and incorporated into the system [29,30].

3.4 Network topology design

Though some FSO networking problems have been studied, topologydesign and optimization have not been investigated sufficiently tothis point. Much of the existing research has been confined to exploringonly issues involving the physical layer. However, recent experimentalsuccesses and technological improvements have enabled researchers toaddress FSO networking problems. The typical problem in networktopology design is what kind of topology should be established, for agiven traffic demand and cost constraints. Topology design andoptimization depend on the specific design objective. In [29,30], authors proposed the bottom-up minimum spanning tree algorithm for designing initial network topology. The authors also propose congestion minimization heuristics to maintain a flexible topology according to the traffic matrix. Topology can be designed for radio channels too. In [28,18,16],researchers explored the future of integrated satellite and terrestrialnetworks including FSO communications. Similarly, in [22,23] investigated where to place a minimum number of FSO links to maximize the capacity of a wireless mesh network andmaximize 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 promisingadvantages due to a very high - frequency band. FSO networks willsurpass wireless radio networks in this capacity since FSO links pose nolimitations on data rate [31]. The FSO links provide acompetitive solution to the “last-mile” problem [9], increasing thecapacity of existing wireless networks [23], and constituting animportant component for the next generation of broadband wirelesscommunication networks [18,29]. In addition to the broadband demand, various QoS requirements,such as end-to-end transmission delay, jitter, packet loss rate, andfairness, should be taken into consideration when designing networkingalgorithms and protocols in FSO networks. For example, the end-to-end delay is an important factor due to the long round trip distancein OWSNs [18], while fairness may be a concern for an OWHN in aroom serving multiple devices. The current congestion control mechanismin the Transmission Control Protocol (TCP) may not work well inan FSO network and could lead to poor throughput performance, andthus 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 regarding network deployment and operation. In OWHNs, a typical IrDA component costs just about 2 USD, which is relatively inexpensive. Hence, it is necessary to further develop transmitters and receivers in consideration of production anddeployment cost. High system costs are discussed in [18], and a system is proposed to develop photon-counting receivers and an air turbulence channels to reduce systemcosts.

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.

IV. Research Challenges

FSO networks have enormous potential for high capacity of overGbps per link. The transmission is normally conducted using a LOSpropagation with a directional narrow beam over a long distance. FSOchannels are deployable on a wide range of areas from home toterrestrial, and to satellite. Those unique properties have sparked alarge amount of research. However, research on fully harvesting thepotential of FSO networks is still in its infant stage, and manyimportant and challenging problems still need to be solved. We discussresearch challenges, existing solutions and open problems in thissection.

4.1 Channel modeling

Such statistical models provide insights on understandingthe FSO channel, which in turn lead to ways to improve suchchannels. As a representative example, we review the log-normal channelmodel to show how link reliability is strongly affected by atmospheric turbulence. Atmospheric turbulence is represented as the refractive index structure parameter denoted as $C_n^{\ 2}$

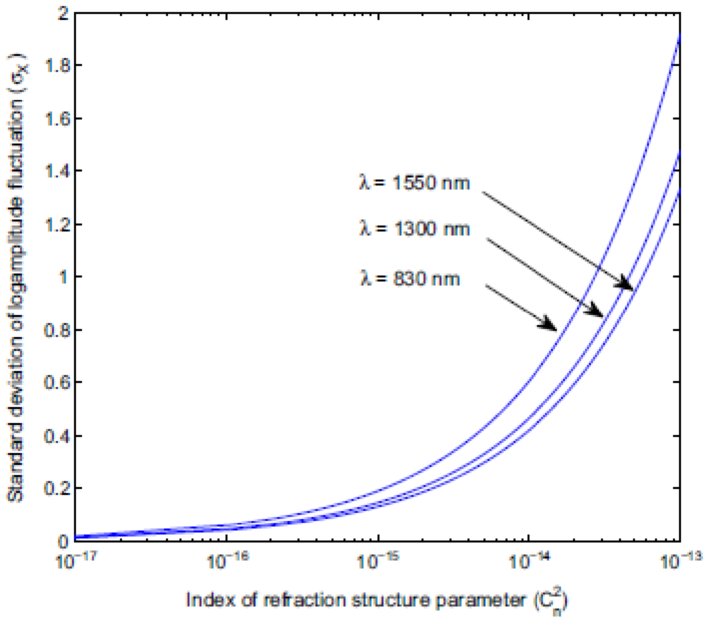

Figure 2: Standard deviation of log-amplitude fluctuation σ_x versus index of refraction structure parameter $C_n^{\ 2}$. The wavelengths are 830 nm, 1300 nm, and 1550 nm, respectively. The propagation distance is 2 km. [19]

4.2 FSO networking

Hardware design is the most focused part of FSO networking; comparably the FSO networking issue is in less attention in the research community. There has been some progressive growth in this aspect [9,18]. Link reliability has been enhanced, and autonomous PAT schemes were proposed [19].

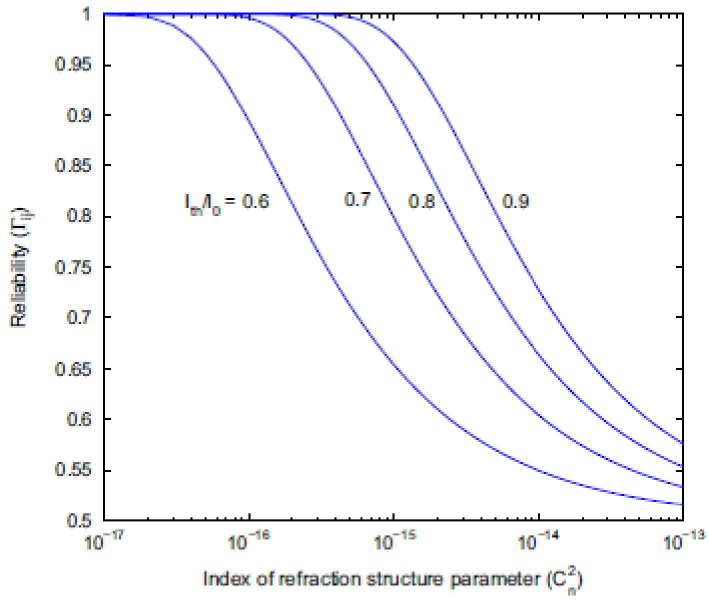

Figure 3: FSO link reliability Γ_{ij} versus index of refraction structure parameter C_n^2. The wavelength is 1550 nm on the 2 km path. [19]

Fig. 3 shows that the link reliability is diminished as weather condition becomes serious (as C_n^2 is increased).

FSO networks have different properties, whencompared to radio wireless networks, which should be taken care of when discussing FSO networking problems.

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

V. Conclusion

In this paper, we presented a survey of FSO networks and communications. We discussed advantages and challenges about it. FSO is ranging from home, to terrestrial, and to satellite optical wireless networks. We provided the state-of-the-art, architecture and a review picture of this future generation wireless technology. We further discussed necessary design factors present in FSO networks. A lot study and discussion have been done about FSO communications for years, but still it is a new topic, and much more research can be done. We provided detailed discussions and challenges of FSO networks. It requires a lot of attention and considerable research effort for practical solutions.

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