

Review

Review on Free-Space Optical Communications for Delay and Disruption Tolerant Networks

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Abstract: The increase of data-rates that are provided by free-space optical (FSO) communications is essential in our data-driven society. When used in satellite and interplanetary networks, these optical links can ensure fast connections, yet they are susceptible to atmospheric disruptions and long orbital delays. The Delay and Disruption Tolerant Networking (DTN) architecture ensures a reliable connection between two end nodes, without the need for a direct connection. This can be an asset when used with FSO links, providing protocols that can handle the intermittent nature of the connection. This paper provides a review on the theoretical and state-of-the-art studies on FSO and DTN. The aim of this review is to provide motivation for the research of an optical wireless satellite network, with focus on the use of the Licklider Transmission Protocol. The assessment presented establishes the viability of these networks, providing many examples to rely on, and summarizing the most recent stage of the development of the technologies addressed.

Keywords: Delay Tolerant Networking; free-space optical communications; satellite and interplanetary networks



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1. Introduction

This review article offers a deep review on Free-space Optical (FSO) communications and Delay-/Disruption-Tolerant Networking (DTN). The combination of these two technologies has gotten off the ground in recent years.

FSO may benefit from DTN as optical links have long disruptions that may impair traditional protocols. The Bundle Protocol (BP), which is the basis of DTN architecture, allows to communicate in challenged networks.

For the past two decades, FSO communications have been considered a viable candidate for wireless networks [1,2], and, as the optical links improve and become more robust, the interest in creating wireless optical networks increases. On the other hand, over 20 years ago, the Jet Propulsion Laboratory of NASA began research on the Interplanetary Network [3], which led to the specifications of DTN [4].

Optical links offer high-speed options for satellite and interplanetary networks. This paper offers a basis of knowledge and summary of research for future applications of these technologies.

Wireless optical networks are of great interest in the research community as optical links provide higher throughput, large available bandwidth, and inherent security robustness to electromagnetic interference. These links reach similar levels of Quality-of-Service (QoS) as optical fiber, and they have the benefit of reaching remote location without the need for the infrastructure of cables. These technologies are also a foundation for future space missions, as optical links provide faster possibilities for the download of

large amounts of data (for example, from visual observation) and communications between satellites, interplanetary probes, and others.

Researching protocols that overcome the disruptions faced by these links is essential to use the maximum capacity of the links, which could not be reached by using the classical protocols for internet. Two distinct scenarios can benefit from these technologies. Firstly, a low-earth orbit (LEO) to ground communication, where the main challenge is the presence of clouds and other adverse weather conditions. Although, for this scenario, the round-trip-time (RTT) is in the order of milliseconds, the use of DTN can be beneficial as outages by clouds can be many orders of magnitude higher. On the other hand, for interplanetary networks, the focus is on the intermittence due to orbital schedule and latency, as the distance between the sender and receiver can be very high; for example, Earth-to-Mars communications have an RTT of 6 to 46 min.

In this paper, the authors use a systematic literature review to identify over 50 published studies, with important information about FSO and DTN. The authors focus on relevant state-of-the-art studies from the years 2015–2021, while also selecting studies that provide base knowledge on the topic from older times. This review has the objective to analyze the feasibility of applying DTN protocols in FSO communications.

This review article is organized as follows. Section 2 provides an introduction to FSO communications with focus on satellite networks and the FSO channel, followed by applications of this technology. Section 3 presents the foundation of DTN, with emphasis on the Licklider Transmission Protocol, followed by the state-of-the-art research on this technology. Finally, in Section 4, possible challenges of the combination of FSO and DTN are considered, followed by conclusions and future work in Section 5.

2. Free-Space Optical Communications

FSO communications are a technology that uses light propagation in air and free-space to transmit information at data-rates higher than those usually achievable by radio-frequency (RF) transmissions. These systems are of great interest, in all application environments where it is not possible to deploy optical-fibers, including, of course, air or space borne systems [5], as shown in the Figure 1.

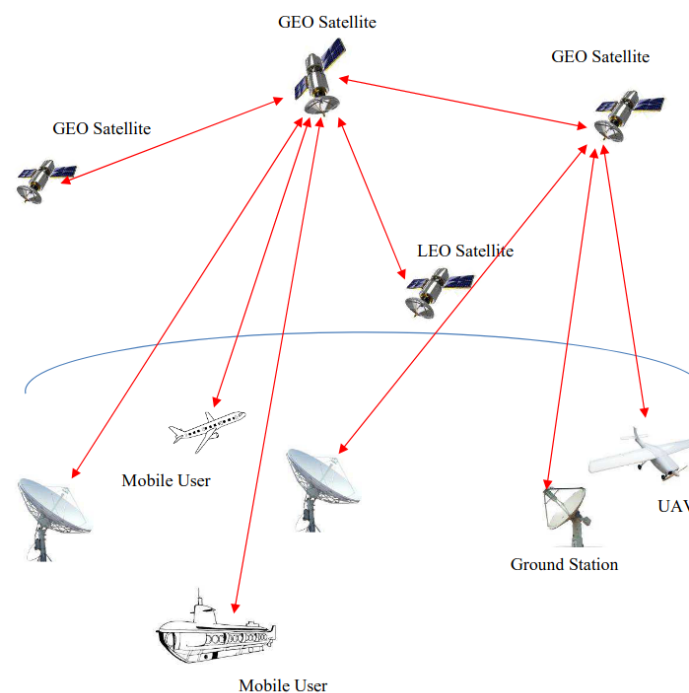


Figure 1. Example of application environments of FSO technologies. Source: Reference [6].

Compared to RF communications, which use electromagnetic waves at a frequency lower than infrared light, FSO provides a higher throughput. Other benefits of this technology are the wider available bandwidth and reduced sized antennas. Optical links have a shorter wavelength; thus, the beam divergence angles are smaller. The very narrow laser beams provide an inherent security and robustness to electromagnetic interference. These systems do not require license fees, and they have lower installation cost [7].

On the other hand, the propagation of the laser beam requires a line of sight for transmission, which means that, if at least one of the end-nodes is on Earth, the communication link can be disrupted by clouds and affected by adverse weather conditions, such as rain.

Transmission in clear-sky conditions can also suffer from some performance degradation because of the induced interference on the light beams, lessening the power received due to the scattering of photons. The wavefront distortion is another effect, as shown in Figure 2, which causes constructive and destructive interference [5].

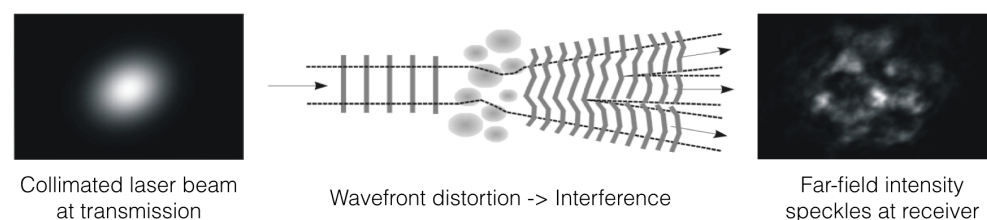


Figure 2. Effects of atmospheric interference on a laser.

2.1. Applications

Lasercom technologies can be used for LEO and geostationary orbit (GEO) satellites, and deep-space probes, between themselves and to ground stations. Inter-satellite links are used in the ESA EDRS system, already operational [8], and in the envisioned ESA HyDRON project [9]. In a longer term, applications will embrace also future networks of airborne or space-borne platforms, including Earth to Moon or interplanetary links.

Optical space networks have to be managed as terrestrial telecommunication networks, but, in space systems, any problem is exacerbated by the inability to easily reach and fix malfunctioning hardware [5]. These characteristics have to be taken into consideration when designing a space network, as the system must have a higher degree of reliability than corresponding terrestrial networks.

2.2. Communication Channel

For a deeper understanding of FSO, one has to examine the channel model, which is affected by two main impairments: atmospheric turbulence and pointing error. These can be studied through statistical analyses.

FSO links, particularly if they include terrestrial atmosphere, present the following properties [10]:

- atmospheric attenuation of laser signals is more severe at low elevation, causing a high variation of received power;
- the link is often blocked by clouds, resulting in long-term fades;
- the amplitude scintillation patterns of received power are in the order of centimeters, which results in fast fades of optical power; and
- the beam in optical communications is very narrow, which can cause an additional source of fading from residual pointing errors of the space terminal.

These characteristics make optical links prone to random disruptions, which add to scheduled intermittence due to orbital motion of space assets. Both disruption and link intermittence require adequate countermeasures at higher layers of the protocol stack as those envisaged by the DTN architecture.

In order to mitigate the disruption, specific link protocols, including error control and Forward Error Correction (FEC) methods, have been designed for FSO links. Mitigation

techniques to common challenges in FSO technologies are summarized in Reference [6,11]. These solutions provide a quality of service to the link for a minimum data-rate, i.e., they can guarantee no losses in the receiver for certain levels of error, nor indicate when the received messages are incorrect. Besides these, higher-layer protocols are used for routing configurations and retransmission [5].

2.3. FSO Links for LEO Scenarios

In a common LEO scenario, the data are downloaded from a satellite that moves in orbit, as seen by a terrestrial observer, to a ground station, which is usually static. As a result of the low orbit and the fast motion of the satellite, contacts are short, in the range of 5 to 10 min. To maximize the use of the short contact time, the connection is exploited at the lowest elevation angle possible, which is between 5 and 10 degrees, thus increasing the possible throughput during each contact. The use of adaptive coding and modulation techniques, which adapt the data-rates to the actual conditions of the link, can provide three times higher throughput than system with a static data-rate, at the expense of an increase in system complexity [12].

Optimizing the throughput at lower angles requires characterizing the power scintillation of the channel, which can be evaluated in a LEO-to-ground scenario. The characterization of the channel phenomena is carried out by means of spatial and temporal statistics over link elevation. During a satellite pass, there is a variation in link distance, elevation angle, slew rate, and the path section of the atmospheric turbulence. The link suffers from atmospheric turbulence, scintillation, and fading, as shown in Reference [13]. The conclusions and specific details of characterization from this paper can be used for practical FSO applications.

2.4. FSO Links in HAPs

FSO links between high-altitude platforms (HAPs) over long distances through the stratosphere have been subject to analysis in Reference [14]. The existence of reciprocity of channel conditions was proven, which promises to be advantageous for FSO systems. By proving the correlation of these links within certain conditions, the channel state information (CSI) obtained has the lowest possible delay, and it can be used to optimize FEC techniques, as well as in adaptive code-rate or data-rate within automatic repeat request (ARQ) techniques.

2.5. High Throughput Achievements

An overview of recent FSO systems that can offer high throughput for satellite-to-ground links is presented in Reference [15]. The world record on transmission speed was set by DLR by reaching a data-rate of 13.16 Tbps over 10.45 km for an FSO link in 2017 [16]. It is also demonstrated that optical technologies are suitable even under challenging conditions. In the recent systems developed, adaptive optics are used to stabilize the uplink channel with pre-distortion techniques, to compensate the effects that the atmosphere has on the link.

GEO satellite relays for optical communications were shown to provide a big return-channel data throughput, with rates in the Gbps range [17]. Implementation ideas for these systems were also presented, namely for the necessary ground infrastructure. The results were exemplified in a case study on the applicability of FSO satellite communications to the radio astronomy community.

2.6. Ground-Station Selection

In Reference [18], the authors outline the development efforts to overcome the lack of current applications of FSO. They survey several ground locations that can support laser communications and detail the basic design of an optical ground station. Systems with FSO links are not limited by their capacity, but they suffer from cloud blockage. In the

design of optical networks, it is crucial select weather-uncorrelated locations first; then, the corresponding layout is used for distance and orbit calculations [19].

Having a larger ground-station diversity is a widely adopted strategy to mitigate the cloud blockage disadvantage [20–22]. More specifically, in Reference [21], the objective was to maximize the transfer of data from a LEO satellite as the criterion to select the ground-stations. In Reference [22], the authors studied how to minimize the number of ground-stations within certain availability constraints of the network. In the state-of-the-art study for this topic, Reference [19], an algorithm is proposed that achieves a better trade-off between network availability and computational complexity, when compared to conventional methods. The selection of ground-stations is formulated as a mathematical optimization problem to maximize the network availability and solved with a method which provides better performance complexity trade-off.

2.7. Optical Wireless Satellite Networks

Traditional satellite networks are constrained by the capacity of RF links, and they may suffer from interference generated by neighboring nodes [23]. By contrast, the small beam divergence angle of FSO links makes them virtually immune to interference. This benefit suggested a research on hybrid RF/FSO systems [24]. The disadvantages of FSO, such as the need for Line-of-sight (LOS) and the losses due to adverse atmospheric conditions, make a fully FSO network unreliable. A hybrid network allows for each type of link to mitigate each other's weaknesses [25].

One of the important applications for optical link networks would be a replacement for wired networks, especially communications over the ocean channels, as they are mostly bared by underwater optical-fiber systems. Optical satellite networks do not need this kind of infrastructure and are then ideal for long distances. They can also provide high data-rate connections for secluded areas or mobile access to remote zones [26].

These kinds of networks can be implemented by state institutions, and they have recently have been a focus of interest for private companies. *SpaceX* is currently deploying a satellite network *Starlink* to provide internet coverage in North-America with a constellation of satellites that provide data-rates of up to 1 Gbps with wireless laser links [27]. This new technology aims to cover rural areas to have access to faster internet.

Although *Starlink* is the most advanced project at the time this paper was written, evaluating by the number of satellites launched, it has other big competitors from big aerospace providers, such as the *Virgin Group*, *Boeing Co.*, and *Thales Alenia Space* [28].

The high potential that direct FSO communications from LEO spacecrafts to Earth hold for upcoming space missions through lower complexity have motivated researchers to study the viability of these systems. That has been carried by defining the end-to-end architecture of lasercom technologies while caring about compatibility with data and system standards [29]. The analysis aims to employ available space protocols for bidirectional optical communications with LEO spacecrafts. The authors of Reference [29] concluded that the implementation of laser communications is manageable in matter of infrastructure to the ground segments. The foreseen challenge is the creation of reliable link schedules with respect to weather conditions and protocols that overcome unanticipated disruptions.

As the links become more robust, development will rely on network and upper layer progress [30–32]. An FSO network can have frequent interruptions, to the point that an end-to-end connection might not be established. This can also happen because of long orbital distances, where the link synchronization happens for limited amounts of time. For these situations, conventional protocols that require an initial end-to-end handshake, such as TCP, cannot establish connection. To overcome this problem, DTN protocols, such as LTP, are an ideal candidate for FSO links, as they skip the initial end-to-end connection phase.

The research and testing of high-speed FSO communication networks has raised interest among many leading groups of investigation. An overview of the current developments and investigation carried on at the NASA Glenn Research Center also shows the requirements and achievements for FSO networks in recent years [33].

3. Delay-/Disruption-Tolerant Networking

DTN originated from a generalization of the requirements of Interplanetary Networking (IPN), when it was identified that the same approach could be applied to challenged networks (where the ordinary TCP/IP architecture has strong drawbacks), on Earth and deep-space [34].

The DTN architecture relies on the introduction of the new Bundle Layer above the Transport Layer (or other lower layers). This overlay depends on the introduction of multiple DTN hops between sender and destination, to deal with long propagation delay and disruption [35].

For the transport layer to interact with bundles, it is necessary to use a convergence layer adapter (CLA) below the BP. The DTN architecture is presented on Figure 3.

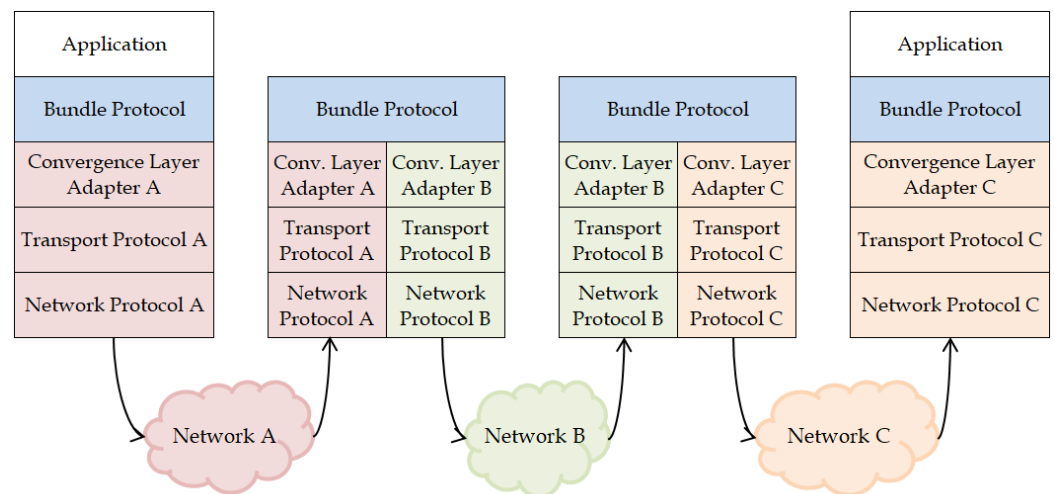


Figure 3. Scheme of the DTN architecture (adapted from Reference [36]). The BP overlays the Transport Protocol, interfacing through a CLA.

In DTN, there is no more need for end-to-end connectivity, in contrast to TCP/IP networks, which stand for Transmission Control Protocol/Internet Protocol. In the presence of link disruptions or scheduled intermittence, the nodes along the path can store the for long periods of time and assure the transfer when the link to the next node becomes available again.

Currently, in addition to IETF on going standardization [37], space standards for DTN systems are promoted by CCSDS (Consultative Committee for Space Data System), a standardization [38] body made by all of the most important space agencies, including NASA, ESA, and DLR. In particular, they have published two “blue books” (the recommended standards) for the Bundle Protocol (BP) [39] and the Licklider Transmission Protocol (LTP) [40].

3.1. Licklider Transmission Protocol (LTP)

The Licklider Transmission Protocol (LTP) was first proposed by NASA for reliable data delivery in challenging space environments, as part of DTN [41]. This protocol was motivated from the need of a retransmission-based protocol that would be reliable over “links characterized by extremely long round-trip times (RTTs) and/or frequent interruptions in connectivity” [42]. It should be used as Convergence Layer of choice in space links, immediately below the Bundle Protocol.

The LTP is applied on DTN, and it supports long-haul transmissions. The bundles are aggregated in LTP blocks, which are split into LTP segments. The blocks are divided in green and red parts, where the green part is unreliably transmitted, and the red transmission is reliable, i.e., the red part requires acknowledgements to ensure its reception [35].

3.2. Advantages of LTP over the Internet Protocol Suite

In space communication channels, characterized by scheduled intermittence, LTP provides reliable data delivery, being widely adopted in systems and simulations. It is commonly researched for the scenario of interplanetary networks, being proposed in literature [43–46], and even deployed in a space mission [47].

The Internet protocol suite, TCP/IP, although successful for the terrestrial operating environments, suffers from strong performance degradation in space long-haul communications, in links with disruptions and high delays. One additional problem is due to the asymmetry of the channel rates, as TCP relies on acknowledgements which require an adequate data-rate in the reverse direction. In literature, comparisons of TCP and LTP have been presented and their performance evaluated in highly asymmetric channels [48,49]. These are valuable studies for the application of high-layer protocols for FSO links, as it is common to have setups with limited uplink data-rates. The main differences between TCP/IP and BP/LTP are summarized below [36,40,48]:

- The use of TCP requires the Internet Protocol (IP), while LTP is compatible with other lower layer protocols.
- In TCP, the **connection** is durable and unlimited in size, while LTP works with size restricted temporary **sessions** for transmission units (LTP blocks)—multiple sessions in parallel are allowed.
- The configuration of the connection in TCP is negotiable by a required three-way handshake, while LTP lacks the connection establishment.
- In TCP, the data is delivered in order within a connection. The nature of a session-oriented protocol, like LTP, manages the delivery of bytes in order within a session but does not guarantee the delivery of LTP blocks in order.
- LTP has a unidirectional data flow, using the reverse channel only for signaling.
- Unlike TCP, LTP does not have any mandatory mechanism for congestion control.
- LTP has a rate-based transmission speed that does not depend on acknowledgements, so losses do not reduce the speed, opposite to TCP which has a window-based congestion control.
- For the red parts of LTP, the acknowledgements—called report segments (RP)—are only sent when requested, or in checkpoints (CP), which are usually on the last segment of the block.

3.3. LTP Performance

Recent studies of this protocol focus on its performance in the presence of link disruptions [50], which is of crucial relevance for its implementation for FSO communications, where the links suffer from burst fading and high delays during adverse weather conditions. In this study, the performance of transmission is predicted for reliable file delivery by an analytical method, focusing on the delay prediction. The research is conducted over communication channels with random link disruptions, long link delays, and high data loss rate.

With the analytical and experimental findings of Reference [50], it was shown that the total file delivery time decreases exponentially with increases in LTP block size. The higher delivery time suffered when using smaller blocks is justified by an increment of latency with each transmission round, worsened when the channel has a higher Bit-Error-Rate.

The study of the memory dynamics in LTP-based communication systems for a deep-space network is presented in Reference [51]. The links emulated are characterized by extremely long delays and asymmetric data-rates. The conclusions presented on the effect of LTP block size show that smaller block sizes allow for a quicker release of occupied memory.

3.4. LTP Enhancements

In Reference [52], the authors propose an enhancement of the LTP protocol that reduces the delays caused by the losses of Report Segments. The improvements were validated by

emulations carried, showing that there is a reduction in the difference between the average and worst case scenario of losses.

In the state of the art of LTP studies, Reference [45]’s researched an implementation of LTP with a Protocol Layer Forward Error Correction (PL-FEC) that decodes errors from unstable links and limits LTP retransmissions to the unlikely case of decoding failures. This FEC protocol is inserted immediately below LTP and called the erasure coding link service adapter (ECLSA). This protocol was upgraded for high-bandwidth-delay links. The High-Speed LTP (HSLTP) “enforces almost one-to-one correspondence between LTP blocks and FEC codewords, and never requires LTP segment retransmissions” [46]. The main advantage is that it requires only one Rx buffer, ideal for nodes limited in memory and optical links in space.

3.5. Tests with a Full Network Scenario

With an emulation based on the Interplanetary Overlay Network (ION) software [53], a virtualized testbed for a DTN of a communication system between Earth and Mars is provided [36]. This system analyzes the performance of the network with the implementation of BP, LTP, and Contact Graph Routing (CGR) algorithm. By analyzing the DTN architecture as a whole, the authors had the opportunity to present a comprehension of the problems from the network. The results drew attention to the role of intermittent connectivity and bundle priority to safeguard the delivery of timely and ordered bundles. The authors show that frequency and volume of contacts increase hop-by-hop. The main challenge of the implementation of these systems is congestion control and network management. A significant safety margin is needed to prevent network saturation. It is also suggested that the LTP aggregation mechanism needs optimization, as well as the code reliability of ION.

This study was realized on a realistic and complex end-to-end scenario, which bridged the research gap of DTN performance evaluation that were focused on individual components of DTN, or simple test cases. This is the case of Reference [54], in which the DTN architecture was used for communication with the International Space Station (ISS), thus validating the flight qualification of DTN software for a simple test configuration.

4. Challenges

The reconfiguration and re-routing of paths can cause significant data processing delays. An FSO system requires a robust routing protocol with minimum delay and small number of hops [6]. This challenge can and should be mitigated with the use of DTN routing protocols.

A possible challenge of the approach FSO+LTP is related to processing speed. Ironically, it actually stems from the major benefit of FSO, i.e., a transfer rate that is 10 times, or even 100 times, to its RF equivalents. Current DTN protocols have not been designed with this speed in mind; thus, their processing, instead of available bandwidth, could represent the new bottleneck.

Artificial intelligence approaches have been used to predict the performance of FSO networks [55], and also as a tool to enhance it, by training an FSO antenna with previous measurements, providing predictions with minimal time delays [56].

In order to do so, a system with DTN protocols and optical wireless links should be emulated, with the use of the platform *Virtual Bricks* [57]. When challenges arise, solutions can be found during an initial phase, before implementing the system for a real setup. This stage allows to develop LTP modifications, although real machines are necessary to test the system with higher data-rates.

Another possible challenge, also related to processing speed, could derive from the adoption of packet-layer FEC, as suggested in Reference [45,46]. These codes could be highly beneficial on interplanetary links, where retransmissions would be very costly in terms of delay, due to the extremely long propagation delay (3–23 min for an Earth to Mars link).

When implementing a new technology, it is of primary importance to create a robust yet simple system, to both overcome the issues that surface and be able to pinpoint the parts of the structure that need improvement.

5. Conclusions

With this paper, the authors provide a basis of knowledge in both FSO and DTN advances. A comprehensive survey on these topics is also presented, mainly on their recent applications. Table 1 presents a summary of the state-of-the-art studies presented throughout the article.

Table 1. Summary of the studies.

Free-Space Optical Communications	
Topics	References
Base knowledge in FSO	[1,2,5,7]
Applications of FSO	[5,8,9]
Communication channel	[6,10,11]
Links for LEO scenarios and HAPs	[12–14]
High throughput achievements	[15–17]
Ground station selection	[18–22]
Satellite networks	[23–26,29–33]
Artificial intelligence approaches	[55,56]
Delay and Disruption Tolerant Networks	
Topics	References
Base knowledge in DTN	[3,4,34,35,39]
LTP and its advantages	[36,40–49]
LTP performance and enhancements	[45,46,50–52]
Full network scenario tests	[33,36,54]

On the topic of FSO communications, a detailed theoretical analysis is provided, followed by research and applications on the links and channel, the ground-station selection, and wireless satellite networks. Furthermore, an introduction to DTN is presented, with focus on the LTP and the state-of-the-art applications of this technology. These technologies show promise for collaboration, with benefits ranging from faster satellite networks to robust protocols for handling the high data-rates.

The challenges proposed will provide a framework for implementing adequate protocols for these kind of networks. The next step for research will be the emulation of a DTN with optical links. This will provide questions and solutions to address obstacles that arise.

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