Free-Space Optical Communication: From Space to Ground and Ocean

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I. Introduction

During the last decade, there has been a rapid advancement in the area of mobile broadband and wireless communication. The demand for higher data rate and capacity has continuously increased thanks to the growing need for information exchange. Currently, the data rates of the existing state-of-the-art radio frequency (RF) or microwave technologies, can no longer meet the ever-growing demand. Therefore, the industry and academia are now exploiting alternative techniques that can provide larger bandwidth and higher data rates. Among different potential technologies, free-space optical (FSO) communication is one of the most promising technologies addressing the problem of large bandwidth and data rate requirements, as well as the last mile bottleneck. Thanks to the various advantages of FSO communication, it can be used in different scenarios from space to ground and under water.

II. Principle and Characteristics

FSO communication works by transmitting modulated laser light through the air between the transmitter and receiver. More specifically, the signal is transmitted using lenses or parabolic mirrors narrowing the light, and projecting it towards the receiver. The emitted light is then picked up at the receiver with a lens or mirror. Subsequently, the received light is focused on an optical detector and converted to electrical signals for further information extraction.

The photo detectors in the receiver are typically semiconductor photodiodes. These have to be tiny to be able to maintain high speeds, as the larger the photodiode is, the slower it becomes. Achieving data rate of gigabit per second requires a photodiode of less than 1 mm^2. However, a laser beam expands further as it travels through space, and can often be much wider than 1 mm^2 at the receiver. This limits the range the beam can travel as the photodiode can only detect a smaller fraction of the signal over longer distances. The typical transmission distance for FSO communication on ground spans from several hundred meters to several kilometers.

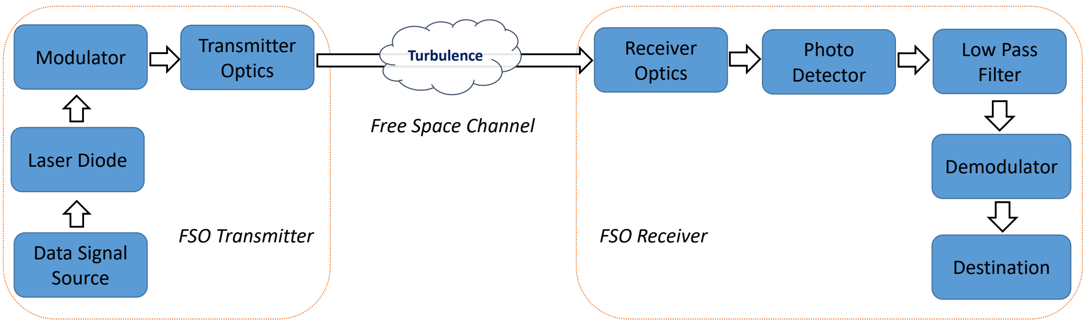

Fig. 1. The structure of a FSO system.

Most wireless systems use the radio frequency part of the electromagnetic spectrum, while FSO communication operates in the visible and infrared (IR) light range. Due to the vastly wide bandwidth and less interference from nearby communication systems, FSO can potentially provide high data transmission rates. In summary, the FSO communication has the following advantages compared to RF communication:

- Large unlicensed spectrum: The terrestrial FSO system operates around the near infrared spectral range from 700 nm to 1600 nm. The large bandwidth available near the IR frequency range promises large potential data rate for FSO communication. With the optical carrier frequency being in the

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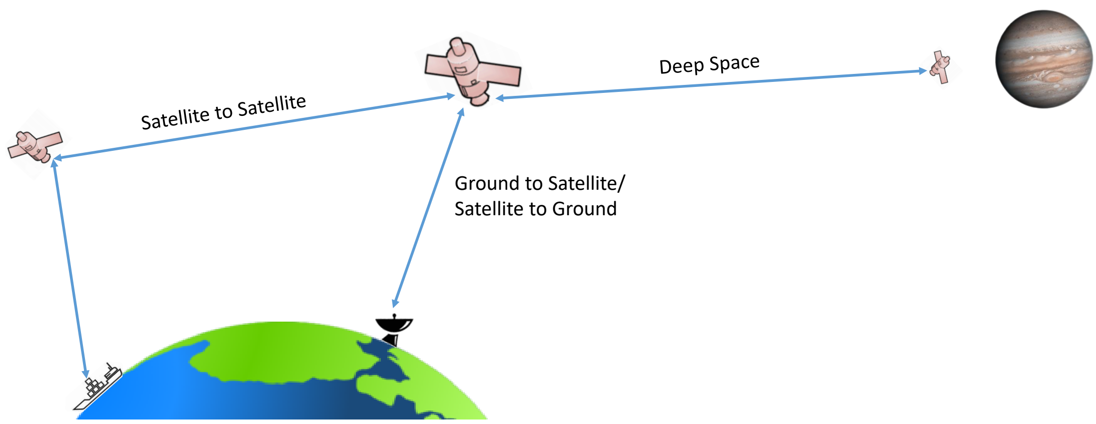

Fig. 2. The use scenarios of FSO technique for space communications.

range of 1012 - 1016 Hz, data rates in the order of Tbps can be achieved with the FSO system. Additionally, this part of the spectrum is not regulated, allowing for cost-efficient deployments and globally applicable solutions.

- High directivity and security: With the extremely small optical wavelength, a very high directivity and improved gain can be obtained. Also, due to its extremely narrow beam width (in the order of mrad), FSO communication can provide less or no interference with enhanced data security. In contrary to RF signals, the line-of-sight transmission of FSO signal can also help to prevent eavesdropping.
- Less power and mass requirements: The narrow beam enabled by FSO communication results in very high signal power intensity at the receiver, which leads to less power consumption. The small wavelength of optical carrier also allows much small antenna size than the RF counterparts.

Overall, the FSO communication is a promising technology with numerous advantages such as low cost, large capacity, and high security.

III. FSO Communication Applications

A. Space Communication

Compared to RF, the advantages of using optical waves in space are reduced weight and volume of the equipment, lower power consumption, higher data rates, and no tariffs or regulatory restrictions as required for RF usage. The continuously increasing number of satellites in orbit is one of the most important motivations for the developments of FSO technology in satellite communication applications. In November 2017, two small satellites were launched to the International Space Station (ISS) to test the latest space-to-ground laser communication system. The first high capacity space-to-ground laser communication system, OSIRIS, was installed in 2018 on the Bartolomeo platform of ISS to enable direct data transfer at the rate of 10 Gbps over the distance of about 1500 km.

The advancements of both space and communication technologies have set the new trends for the future satellite communication. The characteristics of FSO communication make it perfect for some emerging use cases of satellite communication. Some examples are listed as follows:

1) Ground-to-satellite/satellite-to-ground communication:

It is foreseeable that more and more people will be able to travel into space in the future either for scientific or leisure purposes. High-speed Internet access should therefore be guaranteed in manned space stations to leisure activities and entertainment. The scientific experiments conducted in space stations produce massive amounts of data that needs to be transmitted to earth efficiently and securely.

For the scientific experiments conducted in space stations, massive amount of data are expected to be transmitted between the space and ground stations. An optical communication link is a good choice for such purposes. In May 2018, the company ADVA Optical Networking, together with the German Aerospace Center (DLR), made a new record for space FSO communication. The test, which emulated the transmission from a ground station to a geostationary satellite, succeeded in transmitting at the speed of 13.16 Tbps. This clearly shows the great potential of FSO technology for the connectivity between space and ground in the future.

Since both ground-to-satellite and satellite-to-ground communications will pass through the atmosphere, temperatures and pressures of the atmosphere will pose different impacts on the FSO system performance.

Fig. 3. The use scenarios of FSO technique for terrestrial communications.

Specifically, the atmosphere will cause attenuation loss while the FSO signal passes through it. However, the attenuation loss for ground-to-satellite communication is much larger than that of the satellite-to-ground communication due to the different wave model of the source disturbance.

2) Satellite-to-satellite communication:

As the satellites operate far above the atmosphere, the FSO communication for inter-satellite communication is not affected by the adverse atmospheric and weather conditions. However, the successful FSO communication requires accurate alignment of the laser beam between the transmitter and the receiver, this poses a major challenge for the inter-satellite links due to the relative quick motion between the satellites. Besides the challenge on alignment of laser beam, the inter-satellite FSO communication is also limited by other factors such as Doppler shift, satellite platform vibration, acquisition and tracking of received beam, noise from the local oscillator, daytime sky and upwelling radiances.

In late 2018, the Federal Communications Commission (FCC) approved the space data backbone project supported by a consortium of US companies including SpaceX and LeoSat. The project will utilize satellite-to-satellite optical laser links to provide a space-based backbone capable of 1.5 times faster data transfer than conventional terrestrial fiber networks.

3) Deep-space communication:

Deep-space communication refers to the in-space communication over a distance equal to, or greater than 2 million kilometers, as defined by the International Telecommunication Union (ITU). As the performance of the communication system is inversely proportional to the square of the distance, the communication systems used for this purpose has to be energy efficient. Besides the advantages of reduced size and mass compared to RF systems, the narrow laser beam divergence with the capability to provide 10-100 times higher capacity makes FSO an attractive solution for deep space missions.

In October 2013, the Lunar Laser Communication Demonstration (LLCD) project by NASA made history by transmitting data from lunar orbit to Earth at the rate of 622 Mbps, which is about six times more than those of the most advanced radio systems. The historical demonstration of the LLCD project experimentally proved the theoretical conclusion that the next major leap in improving capacity can be achieved by the migration to the optical frequencies. With the momentum of the success from the LLCD project, the researchers are now aiming to use FSO communications from even longer distances such as from Mars or from the Sun-Earth Lagrange Point 2.

B. Terrestrial Communication

The market research institution Transparency Market Research (TMR) predicts that the global market for FSO communication is expected to exhibit a very positive growth trajectory in the forthcoming years. The FSO market is expected to grow from 0.27 billion USD in 2018 to 1.45 billion USD by 2023 with the majority of the growth on terrestrial communication.

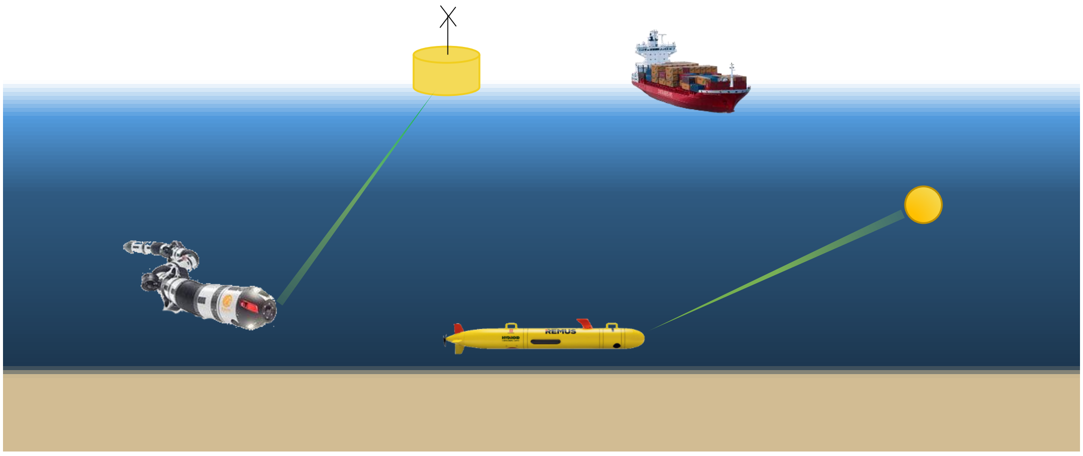

Fig. 4. The use scenarios of FSO technique for underwater communications.

Currently, most of the existing mobile systems exploit the RF bands, where the capacity is limited due to crowded frequency bands. The large license free bandwidth available makes FSO communication an attractive solution for bandwidth-consuming services. For instance, the higher data rate demands for the next generation mobile networks (5G) require backhaul links with much higher capacity than the current. In March 2017, the demonstration of a 100 Gbps data transmission through the FSO link in the air was successfully conducted in Kista, Sweden by a consortium led by the Research Institutes of Sweden (RISE). The high capacity, low cost, and ease of deployment make FSO communication a competitive technique in the 5G backhaul network. The RF backhaul is often limited by latency problem due to the limited throughput but has the advantage of being operational in non-line-of-sight (NLOS) scenarios. The FSO link features high-rate and low latency but it is highly susceptible to the weather conditions and is also limited to line-of-sight (LOS) transmission. To combine the advantages of RF and FSO communications, the hybrid RF-FSO system has been developed as a more reliable solution to be used in the backhaul as an integrated part of the 5G network. The hybrid RF/FSO scheme uses both RF and FSO links for the transmission of data, and can simply adjust the use of both links depending on the wireless interference levels and weather conditions.

Besides being a candidate for backhaul network, FSO can also be used as an access technique to provide high data rate connection in multi-point scenarios, for instance in large organizations. In this case, the FSO system appears as a cost-efficient alternative compared to the conventional fiber optic system in bridging the connectivity with several points within large areas without the need of extensive infrastructure investment. In 2016, Facebook initiated a project that uses FSO communication to provide access to suburban and remote areas. It was proposed that for suburban and remote areas, where building conventional wireless broadband is too expensive, reliable Internet connections can be provided by solar-powered high altitude unmanned aerial vehicles via FSO links.

Despite the great potential of FSO in terrestrial communication its performance largely depends on weather and nature conditions like snow, rain, fog or dust. Extensive measurements show optical attenuation due to rain increases following a power law relationship with rain intensity, while attenuation caused by fog increases exponentially with decreasing visibility. This high attenuation caused by severe weather conditions can significantly reduce the link availability and may lead to link outage. Beside weather conditions, the atmospheric turbulence can also hinder FSO transmission in hot and dry climates. Atmospheric turbulence can induce random changes of the refraction index, which leads to serious fading and phase distortions, thus degrading the performance of coherent receivers. Based on extensive measurements, statistical models such as lognormal, Gamma-Gamma, and Malaga distributions have been used to model the fading caused by atmospheric turbulence. Finally yet importantly, the misalignment due to wind, thermal expansion, and building sways can also degrade the FSO system performance.

C. Underwater communication

Another emerging use scenario of FSO technique is underwater communication. There have been a significant increase in scientific and commercial activities under water, with for instance autonomous unmanned vehicles (AUV) and other devices deployed. Cost-efficient communication system with high throughput is required to handle this growth. While RF communication is ubiquitous in our daily life, the signal transmitted within the RF spectrum are heavily attenuated in water environment. Acoustic communication system is currently prevalent in water due to their ability to propagate long distances. However, achieving high date rate transmission with low latency is difficult with acoustic communication as acoustic energy exhibits much higher attenuations with increasing frequency. Underwater FSO communication have the ability to greatly complement acoustic underwater communication, especially for short-range, mobile, multi-user scenarios.

The underwater FSO channel behaves very different from the atmospheric channel. From the optical communication perspective, the performance of FSO underwater communication is mainly affected by beam absorption and scattering. Absorption results from the transformation of electromagnetic radiation into other sorts of energy like heat. To combat the absorption effect, the wavelength for underwater FSO communication is chosen in the range of violet to blue spectrum (400 nm to 500 nm), where the absorption is at a minimum. Scattering is due to the direction change of photons by means of refraction, reflection, and diffraction. Scattering in ocean water can lead to severe spatial and temporal dispersion, which can pose a measurable impact on link range and available bandwidth. In underwater FSO communication, Mie and Rayleigh scatterings determine the magnitude and direction of the scattered photon. Different from the FSO propagation over air, the turbulence-induced fading underwater are mainly due to random variations of water temperature and salinity. In addition, it was shown that the generalized Gamma and exponentiated Weibull distributions best match the histograms of the measured data.

IV. Future Scope

FSO communication has experienced rapid growth in recent years and the growth is expected to continue in the future. Due to its enormous advantages and its cost effective properties, it is widely believed that FSO will play a larger role in providing high capacity transmission for various applications such as last mile access, back haul for mobile networks, fiber network backup, space to ground communication, and underwater scenario. With the use of UAVs, FSO technology can provide high bandwidth to remote areas. This could have a future application in search and rescue and other disaster relief operations.

To overcome various challenges and hence enhance the system performance of FSO communication, various techniques are being introduced. The methods can be classified into two categories: physical layer methods (e.g., aperture averaging, diversity, advanced modulation & coding, background noise injection and so on) and upper layer methods (ARQ, routing, quality of service control, etc.)

The use of FSO over extremely short distances such as chip-to-chip and board-to-board have also been researched nowadays since it can potentially provide a more advantageous type of interconnection network than the electronic VLSI technology. This can also apply to communication for subcutaneous implants, in which propagation loss due to skin can be compensated by the use of arrays of antennas. FSO also has a potential of replacing patch cords in inter- and intra-rack links in future data center. This could reduce drastically not only the number of cable interconnections, but also the power consumption of the data center.

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