Long-Range Free-Space Optical Communication Research Challenges

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The substantial benefits of free-space optical (FSO) or laser communications (lasercom) have been well known to system designers for quite some time, c.f. [1]. The free-space channel, similar to the fiber channel, provides many benefits at optical frequencies compared to radio frequencies (RF) including extremely wide unregulated bandwidth and tightly confined beams (i.e. narrow beam divergence), both of which enable low size, weight and power (SWaP) terminals. However, significant challenges are still perceived: stochastic intensity fluctuations in a received optical signal after propagating through the atmosphere, power-starved link mode of operation, and narrow transmit beams that must be precisely pointed and tracked.

Since the late 1970's the United States [2], Europe [3] and Japan [4] have actively been developing FSO technology motivated primarily for long-haul spaceborne communication systems. While early efforts were focused on maturing FSO technology, the past decade has seen significant progress toward demonstrating the practicality of FSO for multiple applications. The first high-rate demonstration of FSO between a satellite in Geosynchronous (GEO) orbit and the ground was achieved by the US during the GeoLITE experiment in 2001. A short time later, the European Space Agency (ESA) demonstrated a 50-Mbps FSO link operating at 800-nm wavelengths between their Artemis GEO satellite and: i) another ESA spacecraft in Low-Earth orbit (LEO) in 2001 [5]; ii) a ground station located in Tenerife, Spain in 2001 [6]; and iii) an airplane flying at altitudes as low as 6,000 meters outfitted with an FSO terminal developed by France's Astrium EADS in 2006 [7]. These demonstrations also included successful international interoperability for a GEO-to-LEO link between the ESA's Artemis GEO spacecraft and a LEO spacecraft with an FSO terminal developed and launched by the Japan Aerospace Exploration Agency (JAXA) in 2005 [8].

These early demonstrations provided a basis for operational pathfinder demonstrations being undertaken today. In 2015, the European Data Relay System (EDRS) successfully established a 1.8 Gbps coherent FSO link designed for commercial data transmission from multiple LEO user satellites to a GEO relay which downlinks the optical data via RF to European ground stations [9]. In the US, unique missions planned by the National Aeronautics and Space Administration (NASA) have resulted in some of the most challenging communication requirements for which FSO technology is being developed, c.f. [10]-[12]. For the extreme link ranges required for NASA's deep-space missions, optical beam pointing, acquisition and tracking (PAT) and high-sensitivity receiver requirements are particularly challenging. Also in the US, high-bandwidth readout from airborne sensor platforms requires an FSO link to be established from an aircraft to a ground site through extremely challenging (i.e. nearly horizontal path) atmospheric channels [13], [14]. In addition, tactical FSO links are under development for use in electronic warfare or congested RF spectrum environments for naval ship-to-ship and marine small force communications needs [15].

Fundamental questions about the practicality of FSO communications have been answered and operational systems using FSO technology are under development today. In addition, Government stakeholders are starting to understand how to specify FSO systems and industry is demonstrating it knows how to build reliable FSO terminal technology. Even with this rapid pace of development, research is still needed to enable new applications or improve system utility in the following areas:

1. ***High-Power Uplinks*** for deep-space communication applications. Today, deep-space communication (at ranges beyond ~1M-km) runs through NASA's Deep Space Network (DSN) which is composed of multiple large (e.g. 35-70 m) RF antennas located around the globe. Due in large part to RF spectral constraints and a large number of international spacecraft and rovers being deployed at Mars, the DSN capacity is strained today. NASA's Lunar Laser Communication Demonstration (LLCD) demonstrated 20 Mbps optical uplink rates to a lunar satellite that exceed current RF capabilities by ~5000x and showed that it is practical to use FSO for spacecraft command and control functionality. For future deep-space missions, a high-power uplink capability will be important for enabling mission adaptability and flexibility via high-rate uplink communications for spacecraft performing interplanetary missions. High-power uplinks will also find utility for enabling active pointing, acquisition and tracking (PAT) for deep-space photon-starved FSO links with many-beamwidth point-ahead angles. For an optical uplink propagating through the atmosphere, small and large turbules result in time-varying scintillation and beam wander, respectively. In order to enable high-power optical uplinks through the turbulent atmosphere, research is needed to develop optical reference and power delivery technologies. Optical reference technology research should include terrestrial guide star or space-based (possibly cubesat) optical references with maneuvering capability to provide a downlink beacon through the atmospheric channel between the terrestrial transmitter and deep-space receiver. Optical power delivery research should include high-power optical amplifier and adaptive optics technology development.

2. ***Satellite Formation Flying*** for near-Earth FSO communication and sensing applications. Today, satellites generally operate in a singular manner. Coordinated multi-satellite operations are challenging since spacecraft ranging accuracy is limited and, while multi-spacecraft launch capability exists, orbits are generally not well-coordinated after launch. Future space systems may require satellite formation flying to enable reconfigurable, modular and scalable near-Earth communication and sensing systems that out-perform singular satellites using lower-cost smallsats. Impacts of such a capability include: coherent multi-satellite sensor processing for exo-planet surveys; precision position, navigation and timing (PNT) without a global navigation satellite system (GNSS) and gravity wave sensing. In order to enable fractionated spacecraft formation flying, research is needed to enable FSO crosslinks using wideband signaling enabled at optical frequencies to achieve precision ranging (while simultaneously doing communication) and time transfer. Research targeting improved smallsat technologies will also be required to enable improved station keeping and precision attitude determination and control systems (ADACS).

3. ***Terrestrial Gateway Infrastructure*** for deep-space, near-Earth and airborne FSO communication systems. Today, substantial investment has been made in global RF communication gateway networks by multiple US organizations. In addition, the astronomy community has developed large scientific telescopes that have been adapted for early space FSO demonstrations. In the last five years, NASA's LLCD program developed a 'transportable' optical ground terminal and their LCRD program is exploring 'autonomy' with the GS-2 optical ground terminal deployed at

Maui, HI. For FSO communication technology to be inserted into national-level operational communication systems, development of optical terrestrial gateway terminal network(s) is critical. The gateway network should be capable of providing FSO gateways for space and airborne links and the terminal technologies employed should be cost-effective, modular and scalable and the architecture should be resilient against failure. The gateway network should also provide improved atmospheric turbulence mitigation. Research required to enable these next-generation gateways include development of cost-effective technologies including large-aperture telescopes using emerging optical membrane or multi-aperture coherent combining and turbulence mitigation by well-known adaptive optics or newer multi-mode processing. Reduced operational costs is another important consideration for new optical gateway architectures. Research topics in this area should include inter-satellite crosslink architectures, new network protocols for more efficient traffic processing and simplified ground terminal maintenance and autonomy.

4. ***Multi-User FSO Terminal*** for deep-space, near-Earth space, airborne and terrestrial FSO communication systems. A primary advantage for FSO systems is the narrow optical beam that enables efficient energy delivery and resistance to interference. For FSO systems to find utility for applications beyond wideband point-to-point backhaul applications, the ability to interface efficiently with multiple users is required. Today, RF satellite communication systems such as NASA's Tracking Data Relay System (TDRS) provides low-rate multi-user access via an RF phased array integrated with the TDRS satellites. NASA's LCRD system expected to be deployed in 2019 will be the first "multi-access" optical system with two optical terminals hosted on the LCRD satellite and frame-switching functionality used to forward data frames between different terrestrial- or space-based users. The number of users envisioned for future commercial and military communication systems is expected to increase and FSO technology must be developed to support these applications such as a resilient space-based optical networking node, military theater or hemisphere operations support and efficient support for multiple airborne or terrestrial users. Research in this area should include multi-beam optical transceiver technology, optical phase array transmit and receive technologies, multi-beam opto-electronic feeds and robust routing/switching technologies and protocols.

5. ***Low-Latency FSO Links*** for near-Earth space, airborne and terrestrial FSO communication systems. Due to the large investment in fiber-optic telecommunication networks, emerging FSO systems have generally leveraged fiber-optic components and fiber networking protocols. For unique FSO channel impairments such as scintillation due to atmospheric turbulence, specialized mitigation strategies have been demonstrated, e.g. deep channel interleaving and strong forward error correction (FEC) coding and spatial diversity using multiple optical apertures to sample independent "slices" of the atmosphere. Today, emerging applications that are critically-dependent on low-latency to provide real-time data for commercial applications include high-performance internet data centers and high-frequency stock trading or military applications such as coherent sensor or multi-antenna processing for electronic warfare applications and voice-based command and control applications. The wide bandwidth and interference resistance provided by FSO links is attractive for these applications, but research is required to enable robust atmospheric turbulence performance without the latency incurred

using deep interleaving and coding. Research in this area should include turbulence mitigation by multi-mode processing, reciprocity-enhanced turbulence mitigation, improved turbulence models enabling improved diversity techniques, time synchronization without an RF backbone and new networking protocols.

6. ***FSO Links for High-Performance Networks*** for airborne and terrestrial FSO communication systems. Today, multiple small companies are developing very simple FSO terrestrial terminal solutions for applications where deploying fiber optic cable is impractical (e.g. building-to-building connectivity or airport runway crossing). These terminals generally focus on low-cost optics and modem designs without performance enhancing subsystems such as PAT or atmospheric turbulence mitigation processing. Today, spectrum contention in urban environments and jamming (both unintended friendly communications and active interference by an adversary) in military theaters is a significant issue. In response, new FSO operational prototypes are being developed that will enable higher availability COTS building-to-building FSO links and tactical hub-and-spoke FSO networks for electronic warfare environments. Research in this area should include Layer 2 through Layer 4 protocol development to network many nodes using FSO links, mobile PAT, hybrid resilient communication methods (e.g. trading off RF inter-symbol interference vs FSO atmospheric fading), self-diagnostic channel monitoring with turbulence, weather, temperature, humidity, etc., and smart algorithms (e.g. machine learning, Kalman filtering) to predict channel changes and inform networks.

7. ***FSO Links for Position, Navigation and Time*** for deep-space, near-Earth space, airborne and terrestrial navigation and science applications. Today, GNSS provide position to a few meters and time to a few nanoseconds for terrestrial, airborne and near-Earth space terminals. This capability has enabled a broad range of revolutionary capabilities including precision-strike warfare, train and ship localization, tracking of goods and animals, and myriad sporting applications. Recently, NASA's LLCD showed that wideband optical signaling using FSO links can be used to provide precision time-of-flight measurements with the comm waveform for cm-class ranging to the Moon, beyond the reach of current GNSS. Using FSO links, this capability can be further developed to enable enhanced (e.g. by several orders of magnitude) timing, range and velocity accuracy and GNSS system signaling that is inherently challenging to interfere with. This new capability can also be extended using FSO inter-satellite crosslinks to enable precision formation flying and enable numerous impactful science missions (e.g. Earth and space sciences or gravitational physics). Research in this area should focus on optimally integrating frequency, timing (epoch) and range measurements into FSO communication links with improved understanding and mitigation of atmospheric turbulence effects, optimized two-way protocols and optimized multi-wavelength protocols.

Today, all of the perceived functional challenges associated with FSO communication links for space, airborne and terrestrial applications have been addressed via multiple demonstrations undertaken by the international community. These efforts have resulted in the development of US and European operational pathfinder communication systems for which FSO communication links provide primary connectivity. Despite this maturation, active research is still required for FSO systems and technologies to enable wideband signaling for next-generation deep-space systems, cost-effective terrestrial gateway infrastructure, near-Earth optical FSO networking, and robust PNT for global navigation systems or multi-satellite coordinated formation flying.

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