Coherent Architectures for Free-Space Optical Communications

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Abstract: Custom coherent architectures can provide many advantages for FSO communications systems through co-development of integrated photonics, ASIC- or FPGA-based DSP algorithms, and system design to mitigate atmospheric turbulence and reduce pointing requirements.

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Free-space optical (FSO) links provide the advantages of leveraging large bandwidths and unregulated spectrum to support high-data-rate and/or long-distance links [1]. Fig. 1(a) shows links of interest that include horizontal ground-to-ground links [2-4], space-to-ground links [5, 6], space-to-space links [5, 7], and air-to-ground links [8]. The space-to-space links must overcome diffraction losses and face the challenges of size, weight, and power (SWaP) limitations on both ends of the link. Additionally, links with a ground station face the added challenge of needing to be robust to atmospheric turbulence that leads to scintillation, which can cause significant power fluctuations over millisecond timescales [9]. FSO links must also have sufficient pointing, acquisition, and tracking (PAT) capabilities in order to establish and maintain a link despite any affects related to relative platform motion, platform vibration, and atmospheric scintillation [10].

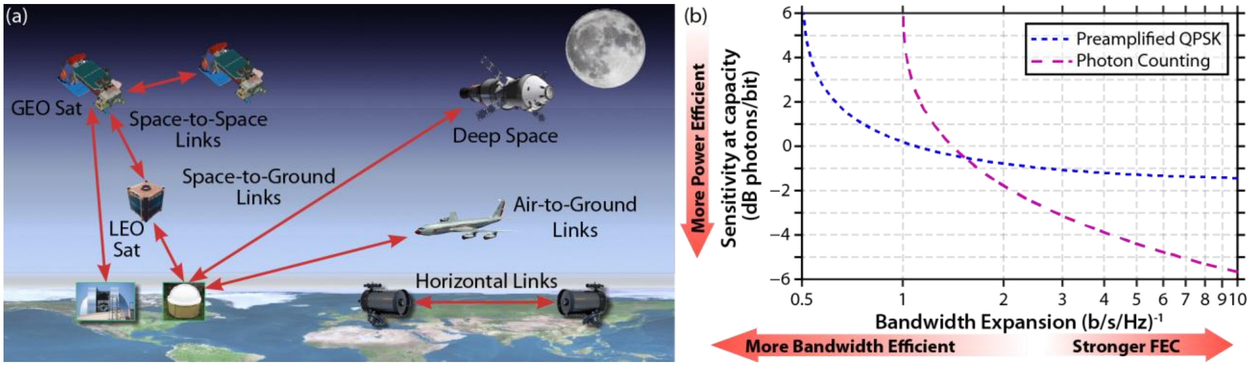

Fig. 1. (a) Example FSO links of interest. (b) Sensitivity at capacity as a function of bandwidth expansion (i.e., FEC utilization). FEC: forward error correction.

Ultimately, FSO links require a minimum number of photons per bit at the receiver in order to close the link. Fig. 1(b) shows sensitivity at capacity for preamplified quaternary phase-shifted keying (QPSK) and photon counting as a function of bandwidth expansion. Long distance links must overcome significant diffraction losses proportional to the square of the link distance that usually limited the achievable data rate. Every 10-dB of additional link distance requires an additional 20-dB from a combination of increased aperture gain, transmitter power, and receiver sensitivity to maintain data rate. As a result, long distance links often use bandwidth-limited photon counting for the ground terminal due to its improved sensitivity over other forms of direct and coherent detection [6]. On the other hand, shorter distance links that can more easily operate at higher speeds (e.g., 100+ Gb/s) using coherent techniques require single-mode fiber (SMF) coupling in addition to suitably fast digital signal processing (DSP) for demodulation, forward error correction (FEC), and atmospheric turbulence mitigation [2, 5, 7].

In particular, coherent communications using binary phase-shifted keying (BPSK) or quaternary phase-shifted keying (QPSK) provide improved sensitivity over direct detection, while supporting significantly increased data rates over systems with single-photon-based receivers [11, 12]. For example, researchers have demonstrated a 5.6 Gb/s LEO-to-LEO link and LEO-to-ground link using BPSK modulation and homodyne detection [5]. Coherent architectures for FSO can be divided into two main approaches: 1) FSO systems leveraging COTS coherent transceiver subsystems that only provide access to digital data bits and the resulting optical waveform, and 2) FSO systems using custom coherent transceiver subsystems. Approach 1) involves directly leveraging COTS coherent transceiver developments and economies of scale from the fiber telecom industry. However, COTS coherent transceiver development for terrestrial fiber networks are designed to handle fiber transmission impairments (e.g., chromatic dispersion (CD), and polarization mode dispersion (PMD)), not FSO transmission impairments (e.g., atmospheric turbulence). In some cases, it is possible to add atmospheric turbulence mitigation to COTS transceivers. For example, in [2], the authors use 100 Gb/s COTS transceivers with an automatic repeat request (ARQ) protocol to mitigate the effects of atmospheric turbulence.

Approach 2) involves the design of custom coherent systems optimized for FSO, which provides maximum flexibility for mitigating atmospheric turbulence. For example, as apertures increase in diameter, D, relative to the atmospheric coherence length, r_0, the effective coupling into SMF decreases. Adaptive optics (AO) helps improve SMF coupling, but becomes increasingly complex with increasing D/r_0. Researchers have shown that multi-aperture digital coherent combining can be used to provide near lossless combining of signals detected from multiple apertures [13]. In this way, multiple apertures can be used as a single effective aperture by digitally combining the full field information between the apertures. Assuming an aperture diameter less than r_0, the relative phase adjustment between the different apertures acts as a form of digital AO that has the potential to scale to an arbitrary number of apertures.

Coherent techniques can also relax the constraint of coupling into SMF by first coupling into few-mode fiber and using an optical device (e.g., photonic lantern or mode demultiplexer) to map the light back to SMF for subsequent detection using multiple coherent receivers [3, 4, 14]. As the fiber diameter increases to support more modes, the effective field-of-view of the fiber increases making the receiver more tolerant to coupling errors, and the coupling efficiency increases slightly over SMF coupling due to the additional modes with significant energy centered in the fiber core [15]. Researchers have shown that after propagation through a 1.6-km FSO link, coupling light into a 3-mode FMF without any tip/tilt correction provided a smaller standard deviation and greater mean received power vs. SMF coupling. In other words, coupling light into few-mode fibers reduces the amount of tip/tilt required for a system, which reduces the requirements for PAT system.

Custom coherent architectures for FSO communications provide a path for optimizing mitigation of atmospheric turbulence and easing PAT system constraints. Key aspects for facilitating coherent architectures based on multiple apertures and/or multi-mode coupling involve the close development of integrated photonic coherent receiver arrays and real-time DSP. A wide variety of configurations become possible for FSO communication leveraging coherent technology that will vary as a function of atmospheric turbulence.

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