Free-space Optics for Communications at Sea

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Abstract: We discuss our free-space-optical communication system, specifically exploring tradeoffs in pointing, acquisition, and tracking design and the use of retransmission to mitigate the impact of turbulence-induced fades. © 2022 The Authors

1. Introduction

Free-space-optical (FSO) communication provides several advantages over traditional radio frequency links, including much higher bandwidth (carrier frequency of 192 THz vs ~GHz) and much more directional beams (order of 100 µrad). In addition, FSO systems operate in a currently unregulated spectrum, allowing for many users to operate on the same frequency without interference. The same physical characteristics that provide these benefits also present challenges to system designers. The highly directional laser beam requires high precision pointing, acquisition, and tracking (PAT) to maintain the system alignment needed to efficiently couple the light from the transmit fiber into the receive fiber on the far side of the link. These challenges are compounded on moving platforms where the PAT system must compensate for platform motion as well as for beam wander due to the atmosphere. In addition, highly directional optical links are known to suffer from degradation due to inhomogeneities of the index of refraction (turbulence) along the line-of-sight path. These variations can produce beam spread, beam wander, as well as constructive and destructive interference (fades) at the receiver [1]. These fluctuations can be greater than 30 dB on millisecond timescales.

Johns Hopkins University Applied Physics Lab (APL) designed, fabricated, and demonstrated an FSO system in static and mobile configurations, in desert, temperate, and maritime environments, and under a variety of weather conditions with over 400 hours of collective test time. We tested our system in three maritime environments including, (1) static to static over the Chesapeake Bay in MD [2], (2) static to mobile over the Delaware Bay [3], and (3) static to mobile and mobile to mobile off the coast of San Diego, CA [4]. Here we discuss tradeoffs in the optical power allocated to PAT versus the data beam, and the use of retransmission and quality of service (QoS) to mitigate the impact of turbulence-induced fades.

2. Terminal Design Considerations for Data Beam Tracking

We use a nested approach to closing the link between one or more mobile platforms [3]. To establish coarse pointing, the outer loop uses an alternate channel (i.e., radio, cell phone) to exchange GPS coordinates between platforms. We have also demonstrated acquisition using *a priori* knowledge of the starting location or visual line-of-bearing information to establish coarse pointing. Once the two terminals are pointed at each other within 3 degrees, a short-wave infrared (SWIR) beacon and camera system are used in conjunction with an inertially stabilized gimbal to compensate for the platform motion. Finally, the data beam tracking is performed with a quad detector and a fast-steering mirror (FSM) to provide first order (tip/tilt) adaptive optics correction on the scintillated beam. The APL terminal consists of a custom optical payload integrated into a commercially available General Dynamics Vector 20 maritime gimbal, as pictured in Figure 1.

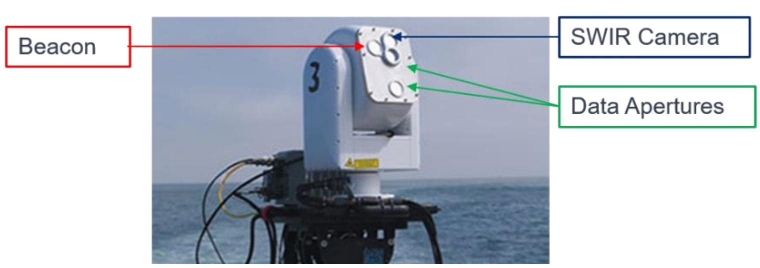

Figure 1. The APL optical terminal is housed in a General Dynamics Vector20 maritime gimbal. There are two bidirectional data apertures (simultaneous transmit and receive through both data apertures), a beacon aperture (transmit) and a camera aperture (receive) on the front of the gimbal.

The SWIR beacon is co-aligned to the data beam but purposefully diverged to increase the acquisition angle at the remote terminal. The camera collects images of the beacon and is optimized to maximize the signal-to-noise ratio of the remote beacon in the video frame. We use a blob detection algorithm to identify the beacon and command the gimbal to make pointing adjustments. One additional challenge presented by maritime links is occasional impulse-type platform motions caused by choppy waves. If the platform motion is large enough to cause the data tracking loop to fall out of lock, the video tracking loop allows link reacquisition within fractions of a second.

We chose a monostatic optical payload design to simplify the optimization of the data beam tracking through path reciprocity. The data tracking loop uses the incoming light as the feedback mechanism to steer the outgoing beam. One disadvantage of the monostatic terminal design is that sufficient isolation between the transmitted and received signals is difficult to achieve. We use two different wavelengths for transmit and receive, along with filters and a high-isolation circulator. However, cross-talk from the outgoing beam still exists on the received path, and reflections inside the terminal pose a challenge to the data beam tracking as well.

Often, data beam tracking for FSO systems use a detector in a feedback loop with an FSM to provide the tip/tilt correction needed to guide the incoming beam into the data fiber. Our system uses a 90/10 beam splitter to divert 10% of the incoming light away from the data fiber and onto a quadrant detector for tracking. For our ship-to-shore experiments, we had a maximum range of 45 km limited by the curvature of the earth. At this range we observed that the received power was above the receiver sensitivity. However due to our choice of a 90/10 ratio between data and tracking power, the fine tracking loop had insufficient power at longer ranges. Thus, the data transmission at the longer ranges of the experiment were forced to rely on the video tracking loop alone to maintain the link.

It is common for PAT to be the range-limiting element of an FSO link, as opposed to received power level. System designers must weigh the tradeoffs between monostatic and bistatic architectures as they relate to PAT, as well as tradeoffs in maximizing the light sent back to the data fiber while providing the tracking system with a healthy signal at the same time. Ultimately, the wider bandwidth of the free space filter used on the quad detector in our system limited the isolation between the transmit and receive beams. This design choice resulted in a higher noise floor at the quad detector that limited the tracking capabilities at long ranges. In later designs, we have worked to address these issues to produce a more robust data tracking solution.

3. Retransmission for Graceful Link Degradation

Perhaps one of the greatest barriers to the widespread use of FSO communications is the effect of the atmosphere and weather on these links. Scattering, absorption, and turbulence all limit the transmission of the optical beam through the free space channel [1]. This can be especially true in maritime environments. One experiment comparing SWIR visibility of an over-water link to the same equipment operating in the desert showed that the desert link had almost twice the visibility as the maritime link [5]. While absorption and scattering effects directly equate to a link budget penalty, turbulence creates changes in the index of refraction of the air, causing constructive and destructive interference (scintillation) of the transmitted signal that can result in dynamic power fluctuations of 30 dB on millisecond timescales at the receiver. A successful optical communications system operating in an environment with strong turbulence and the risk of poor weather conditions must be prepared to fail gracefully rather than be designed to fully overcome these obstacles.

We use a layer 2 packet retransmission protocol with buffering to provide resilience to the atmospheric fades that are expected in an FSO link in a maritime environment. The primary metric reported by the retransmission system is link availability, which we define as the percentage of successful cyclic redundancy checks (CRCs). Our retransmission protocol implements a standard G.709 forward error correction code with a threshold of 10^{-3} bit error rate tolerance. When the received power in fiber (PIF) is above the sensitivity threshold of the receiver, the CRCs will pass, resulting in error free data transmission. When the received power is below the sensitivity threshold, this is considered a power fade, and the data sent during that time window will be lost. In this case, the CRC will fail, and the system will automatically resend the lost data until a successful CRC is acknowledged by the far side of the link. Therefore, the link availability can be viewed as the percentage of time PIF is above the receiver sensitivity level. The retransmission also reports buffer levels, which are related to both the link availability and the link utilization (amount of data currently being sent across the link). Rising buffer levels are an indication that the link cannot support the current data throughput indefinitely with the current link availability. Quality of service (QoS) protocols allow the user to designate high priority data so that as the demand for bandwidth outpaces the channel availability, the data is prioritized appropriately.

Figure 2 presents data from June 2017 demonstrating a graceful link degradation using retransmission. This data was taken from the sea-based platform in a ship-to-shore configuration. The x-axis for all plots is time, with a run duration of just over two hours. The top waterfall plot shows one-second histograms of PIF. The second plot shows a one-second average link availability from the retransmission system. The third plot shows the distance between the two terminals as the ship moved away from the land based site. The black dotted line notes the point at which 2 Gbps of bidirectional traffic was stopped in order to prioritize the low-rate VoIP traffic providing the primary means of communication with the land site. VoIP traffic continued out to ~35 km, at which point the outages were too frequent to carry on a voice conversation. Text based messages worked out to 45 km which was the line of sight limit for this test. At the time of this test, QoS protocols had not been implemented in our system, so the operators were manually adjusting traffic to allow the highest priority data to make it across. These results demonstrate a graceful link degradation that allows data rate to be traded for additional link distance or resilience against adverse environmental conditions.

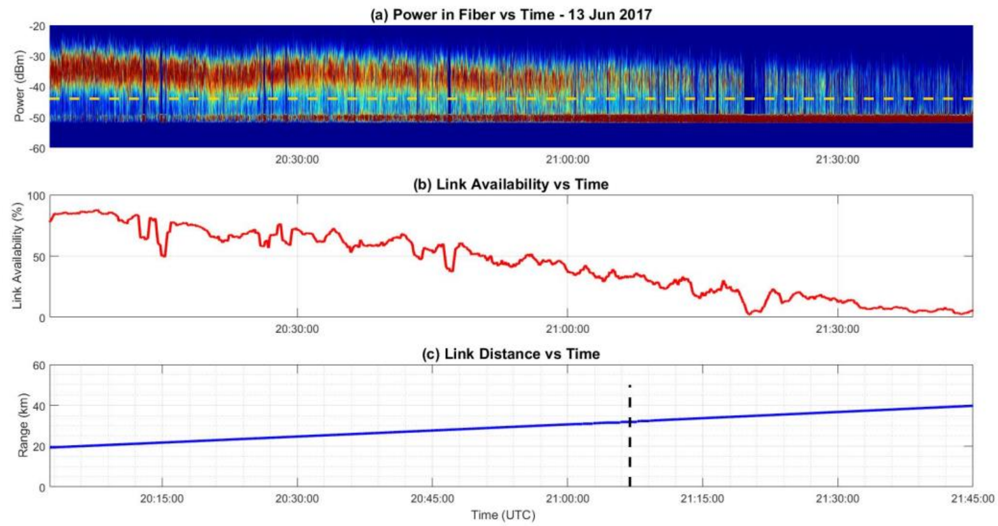

Figure 2. Data collected June 2017 in a ship to shore configuration; (a) One-second histograms of PIF compared to the receiver sensitivity (-44 dBm) in yellow; (b) One-second moving average link availability recorded by the retransmission system; (c) Distance between two terminals during the test run. 2 Gbps bidirectional data tested out to 30 km (black dotted line)

4. Conclusion

The FSO system designer is faced with many tradeoffs to consider in the design of an optical wireless link. While different solutions may be required to meet the needs of various domains – including sea, air, land, and space – some common lessons apply. Considering the atmospheric effects on the optical beam, a nested pointing, acquisition, and tracking approach will be beneficial in both air and sea systems, providing the means for robust link re-acquisition following an extended fade or line of sight blockage. Retransmission along with quality of service will allow maximum flexibility in operating these links in various environments. We have demonstrated a system over land and sea with a modular architecture that could be scaled up or down to accommodate alternate platform requirements.

5. References

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