Demonstration of a 4.2km MISO free-space optical communication link using COTS SFP+ transceivers

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ABSTRACT

We report the design and field testing of a retroreflector-based multiple-input single-output (MISO) free-space optical communication (FSOC) link employing commercial off-the-shelf transceivers. A four-transmitter architecture operating in the C-band is demonstrated over a 4.2 km round-trip optical path, achieving a sustained TCP throughput of 8.43 Gbps. The system incorporates optical amplification and a beacon-assisted multi-level auto-alignment scheme to mitigate link loss, misalignment, and atmospheric turbulence. Long-duration measurements are performed to experimentally characterize throughput performance and turbulence-induced power fluctuations under real outdoor conditions.

Keywords: MISO, FSOC, COTS, SFP+

1. INTRODUCTION

The widening digital divide between urban and rural areas remains a major challenge for modern telecommunications. Deploying fiber networks in sparsely populated regions is often prohibitively expensive, making wireless optical communication a practical and cost-effective alternative for high-capacity backhaul.[1] Operating in the infrared spectrum, free-space optical communication (FSOC) links can achieve fiber-like data rates without the need for trenching or cabling, making them attractive for last-mile connectivity in remote environments.[2] However, atmospheric turbulence, beam wander, and fog-related attenuation can severely degrade link stability and throughput. Conventional single-input-single-output (SISO) architectures are particularly vulnerable, exhibiting multi-decibel power fluctuations over millisecond timescales. Recent computational advances have improved FSO link resilience. Neural networks trained on real atmospheric data can predict turbulence behavior for proactive beam correction, while machine-learning-based tracking algorithms reduce acquisition time to seconds under dynamic conditions. Rate-adaptive modulation further maintains link quality through weather variations. Spatial diversity provides another effective solution: by transmitting identical data through multiple apertures beyond the atmospheric coherence length, multiple-input-single-output (MISO) systems reduce deep fades and enhance link robustness.[3] Despite these developments, few real-world field experiments have demonstrated such techniques using commercial hardware under variable weather and deployment constraints, leaving a gap between controlled laboratory demonstrations and practical MISO-based FSO implementations.[4]

In this work, we present the design and experimental validation of a four-channel MISO FSOC system based entirely on commercial 10 Gbps SFP+ transceivers. The system operates in the C-band and employs a 1×4 optical splitter with carefully equalized arm lengths to minimize inter-channel timing mismatch. Optical amplification is used at both the transmitter and receiver to compensate for link loss and turbulence-induced fluctuations, while a beacon-based multi-level auto-alignment system ensures long-term pointing stability. A retroreflector terminal is deployed to form a 4.2 km round-trip optical path, enabling long-duration outdoor measurements. System throughput and received power statistics are analyzed to assess link performance and atmospheric impact under practical deployment conditions.

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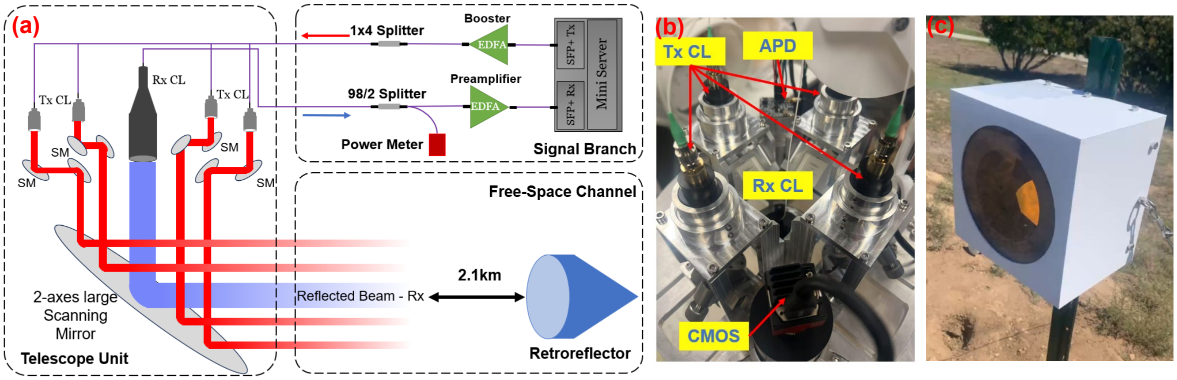

Figure 1. (a) Schematic diagram of the retroreflector-based MISO free-space optical communication (FSOC) link over 2.1 km. (2) Top view of the telescope assembly showing the beacon reception system equipped with an APD and a CMOS camera. (c) Retroreflector terminal deployed 2.1 km away from the telescope site.

2. SYSTEM DESIGN AND EXPERIMENTAL SETUP

The telescope units are custom-designed, in-house-built devices assembled in a laboratory environment using various off-the-shelf, commercially available components commonly used in photonic and optical communication systems. The architecture of the system is shown in Fig. 1 (a). The telescope is equipped with 4 Tx arms, enabled by a 1×4 splitter and 4 optical collimators (CL) with a divergence angle of 0.1 mrad. The 1×4 splitter is customized with four equal-length splitting arms of 75 cm each. Additionally, the housing of the collimators are made adjustable to ensure timing accuracy better than 20 ps among the Tx branches. Moreover, each Tx collimator arm includes two steering mirrors (SM) mounted on precision kinematic stages to eliminate regular misalignment between the Tx channels. The splitter is dividing the common source signal generated from Single Mode Fiber (SMF) SFP+ transceivers (with Rx sensitivity of -24 dBm). To amplify the transmitted signal, a booster Erbium-Doped Fiber Amplifier (EDFA) with 35 dBm saturated output power is integrated into the system, ensuring reliable long-range terrestrial connectivity. In the receiver branch, a larger-size collimator (55 mm diameter) is then placed in the middle of the telescope to couple the incoming Tx beam. a 98/2 optical power splitter is utilized, directing 2% of the signal to an optical power meter for reception power acquisition. Again, to boost the signal above the receiver sensitivity, the remaining 98% is fed into an preamplifier EDFA to further amplify the received signal to 0 dBm, operating at Automatic Power Control (APC) mode. To verify the link performance, the SFP+ transceiver is activated via a mini server, which executes the *iperf3* TCP throughput measurement.

The self-alignment beacon system, on the other hand, has been developed to mitigate the reductions in fiber coupling efficiency caused by incidence angle mismatches, beam walk-off, and weather-induced turbulence. As shown in Fig. 1 (b), a 980,nm beacon laser carrying 10 kbps data to establish the link is transmitted via the receiver collimator and combined with the signal beam using an optical combiner to maintain coaxial alignment. Since the Rx CL is optimized for the signal transmission in the C-band, the beacon beam exhibits significant divergence angle, making beacon alignment comparatively easier. The self-alignment system employs a two-axes large-mirror configuration, where each axis is actuated by a stepper motor with 0.5 nm positioning accuracy, corresponding to an angular resolution of approximately 0.006 µrad per step. This configuration enables precise bidirectional steering of the telescope for dynamic alignment correction. Within the beacon receiver, dedicated lens assemblies direct the beacon light onto a silicon (Si) avalanche photodiode (APD) for low-speed data detection and a CMOS camera for fine tracking. Together, these components provide a ±6 degree field of view (FoV) and an angular resolution of 30.2 µrad. A detailed analysis of beacon alignment performance is further explained in a past paper.[5] The self-alignment algorithm processes data from the APD (coarse alignment), CMOS camera (fine alignment), and power meters (ultra-fine alignment) in the signal branch to dynamically control the motorized stages, ensuring stable and reliable link connectivity. The telescope is installed on a rooftop within the campus of the University of California, Irvine. To establish a long-distance optical link with a clear line of sight, the corresponding retroreflector terminal, shown in Fig. 1 (c), was deployed 2.1 km away from the

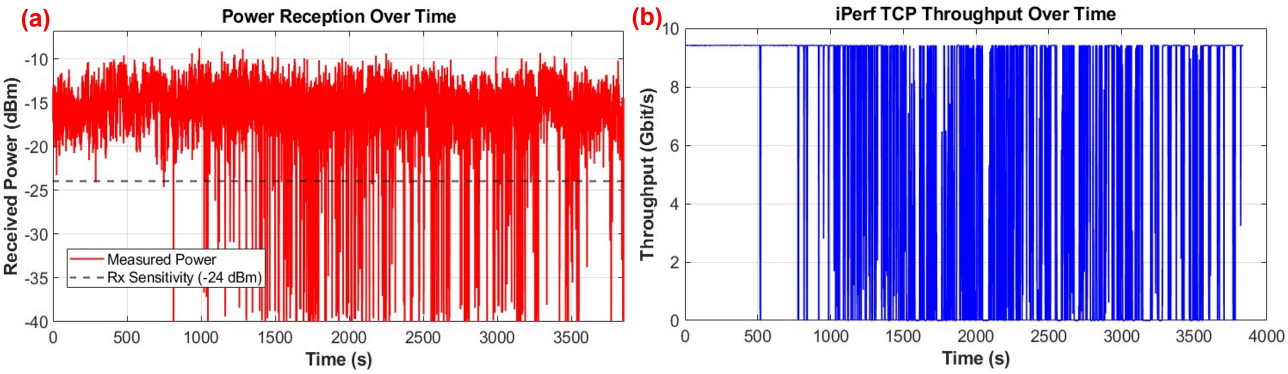

Figure 2. Measured link performance of the 4.2 km retroreflector-based FSOC system. (a) Received optical power over time. (b) Corresponding iPerf3 TCP throughput over the same measurement period.

telescope site to reflect both the signal and beacon beams back toward the receiver for link verification, resulting in a total optical path length of 4.2 km.

3. EXPERIMENTAL RESULTS

To evaluate the performance of the retroreflector-based MISO FSOC system, we conducted extensive field measurements over the 4.2 km link, collecting continuous power measurements and throughput data. The MISO configuration employs multiple transmit apertures at the telescope site communicating with a single retroreflector terminal, enabling spatial diversity to mitigate atmospheric turbulence effects.

Figure 2 presents synchronized measurements of received optical power and TCP throughput performance over a 4000-second observation period. As shown in Fig. 2(a), the received power exhibits significant fluctuations ranging from -10 dBm to -35 dBm, with the receiver sensitivity threshold marked at -24 dBm. Since the retroreflector cause the beam return to the Tx collimators, Rx collimator only collects the tails of the expanded beam, and collected power is lower than a real 4.2km bidirectional link. However, we can directly correlate these power variations with the TCP throughput shown in Fig. 2(b), where we achieved an average throughput of 8.43 Gbps and a maximum throughput of 10 Gbps using textitiperf3 TCP testing. The throughput demonstrates high stability during periods of sufficient received power, maintaining consistent rates near 8 Gbps when the signal remains above the sensitivity threshold. However, severe power drops below -24 dBm result in complete link outages, visible as throughput falling to 0 Gbps at multiple instances throughout the measurement period. To quantify the impact of atmospheric turbulence on link performance, we analyzed the relationship between

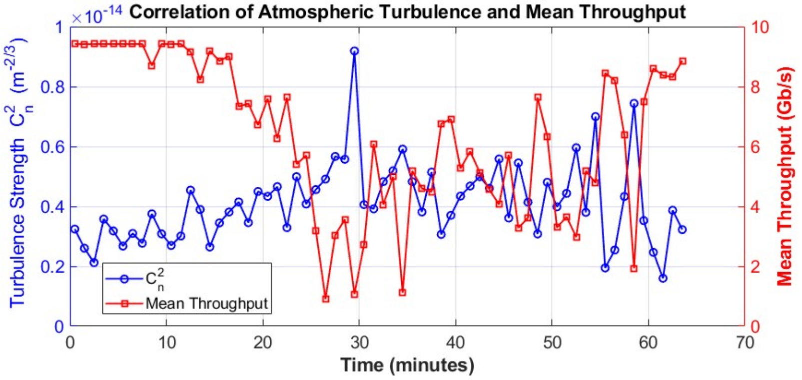

Figure 3. Correlation between turbulence strength (C_n^2) and mean throughput of the 4.2 km FSOC link, showing a strong negative correlation ($R = -0.78$).

the refractive index structure parameter C_n^2 and mean throughput. Figure 3 illustrates this correlation over a 64-minute measurement window. The C_n^2 values, calculated using the Log-Normal turbulence model, range from 1×10^{-15} to 10×10^{-15} $\mathrm{m}^{-2/3}$, indicating moderate to strong turbulence conditions. The corresponding mean throughput varies inversely with turbulence strength, decreasing from approximately 9 Gbps during weak turbulence ($C_n^2 < 3 \times 10^{-15}$ $\mathrm{m}^{-2/3}$) to as low as 1 Gbps during strong turbulence events. The strong negative correlation coefficient of $R = -0.78$ demonstrates that atmospheric turbulence is a primary limiting factor for FSOC system performance. The MISO configuration provides improved resilience compared to traditional SISO systems by leveraging spatial diversity, though significant throughput degradation still occurs during severe turbulence conditions.

4. CONCLUSION

We demonstrated a 4.2 km retroreflector-based MISO free-space optical link using COTS SFP+ transceivers, achieving 8.43 Gbps TCP throughput with <25 ps timing accuracy among the Tx branches. Field results show a strong negative correlation ($R = -0.78$) between turbulence strength and throughput, indicating that while spatial diversity improves link robustness, fluctuations due to atmospheric turbulence and misalignment still impose performance limitations.

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