2025 European Conference on Optical Communications (ECOC) | 979-8-3315-9531-9/25/$31.00 ©2025 IEEE | DOI: 10.1109/ECOC66593.2025.11263248

Long-Range, High-Capacity FSOC System for Rural Wireless X-Haul Using COTS Transceivers

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Abstract *We present a 10.15 km long publicly available free-space optical communication testbed using commercially available multi-channel 10G-SFP+ transceivers deployed in rural Iowa, USA. The effective bit rates, scintillations, and channel dropout rates are studied. ©2024 The Author(s)*

Introduction

As a promising future solution, Free-Space Optical Communication (FSOC) has garnered increasing attention recently due to its fast and cost-effective deployment[1]. FSOC systems offer high-speed data transmission over long distances without requiring large-scale infrastructure, making them a viable solution for wireless x-haul applications in rural areas. However, long-distance terrestrial FSOC links face multiple challenges, including beam misalignment, weather-induced atmospheric turbulence, and scattering attenuation. Various research efforts have explored solutions such as beam positioning systems for alignment using control signals and neural networks[2], turbulence prediction using machine learning[3], and adaptive modulation schemes such as Rate-Compatible Modulation (RCM) to counter weather effects[4]. A demonstration of Tbps bit-rate coherent FSO data transmission has also been conducted at 1.8 km[5]. Nevertheless, the studies mentioned above neither successfully established a functional link in a rural area nor utilized Commercial-Off-the-Shelf (COTS) transceivers and switches to demonstrate real-world communication.

In this work, we present publicly available *AraOptical*, deployed in the rural agricultural region of Ames, Iowa, spanning a distance of 10.15 km. The AraOptical link operates at 194 THz in the C-band and is equipped with commercially available switches and Small Form-Factor Pluggable Plus (SFP+) transceivers. The AraOptical telescope is integrated with a beacon alignment system that employs a multi-level (coarse/fine/ultra-fine) self-alignment algorithm to ensure precise link alignment. Furthermore, we integrated AraOptical as a key component of the ARA[6], an at-scale wireless living lab in Central Iowa for advanced wireless research, establishing a pioneering heterogeneous wireless x-haul platform that facilitates advanced research and experimentation on long-range FSOC systems in real-world rural environments. Using the AraOptical platform, we collected extensive firsthand data, allowing a detailed analysis of scintillation effects and misalignment on the effective bit rate. The AraOptical platform is publicly available for experimental demonstrations of new algorithms and transceiver architectures aimed at improving the robustness of FSOC systems, as well as custom heterogeneous integration experiments.

System Design

The AraOptical 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 AraOptical system is shown in Fig. 1. The two optical nodes are installed in Ames, Iowa, on the roof of Residence Hall, a student residence building, and at Agronomy Research Farm, respectively. Each node is equipped with 16 10G-Base-ZR (Ze Best Range) Dense-Wavelength-Division-Multiplexing (DWDM) and Single Mode Fiber (SMF) SFP+ transceivers (with Rx sensitivity of -24 dBm) operating at distinct wavelengths via a Juniper ACX710 universal metro router, which is directly connected to the optical DWDM module. The optical DWDM module functions primarily as a multiplexer and de-multiplexer for the transmitted and received optical signals. To amplify the transmitted signal, an Erbium-Doped Fiber Amplifier (EDFA) with 33 dBm saturated output power is integrated into the system, ensuring reliable long-range terrestrial connectivity. In the receiver branch, a 98/2 optical power splitter is utilized, directing 2% of the signal to an optical power meter for real-time feedback to the control algorithm. To mitigate losses and fluctuations induced by weather turbulence and potential misalignment, as well as to enhance reception power beyond the receiver sensitivity of the SFP+ transceivers, an additional Low-Noise pre-Amplifier (LNA) is incorporated. After the splitter, the remaining 98% is fed

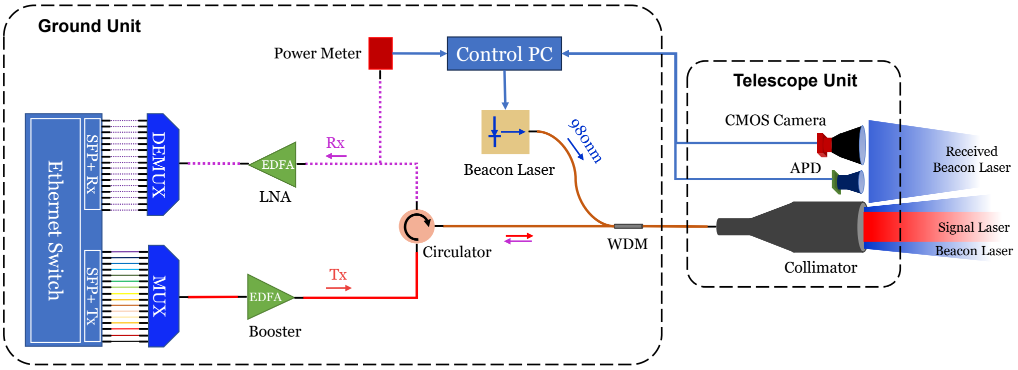

Fig. 1: System architecture of AraOptical

into an LNA to further amplify the received signal to 0 dBm before de-multiplexing, maintaining link stability. For over-the-air transmission, an optical collimator featuring 35 $\mu\mathrm{rad}$ divergence angle is used to enhance the transmission capacity and minimize geometric losses.

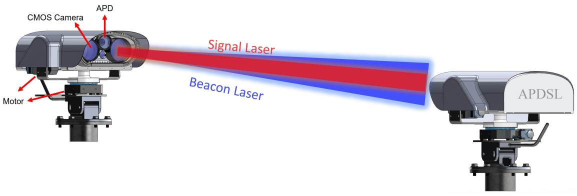

Fig. 2: Multi-level self-alignment system of AraOptical

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, a 980 nm beacon laser carrying 10 kbps data to transfer essential alignment commands is multiplexed with the signal beam using a WDM to prevent misalignment between them. Since the CL is optimized for the signal transmission in the C-band, the beacon beam exhibits significantly greater divergence than the signal beam, making beacon alignment comparatively easier. Fig. 2 provides a visualization of the self-alignment system. It is supported by a custom-designed mechanical housing, and it utilizes two high-resolution motorized rotational stages, each capable of 0.23 $\mu\mathrm{rad}$ per microstep, enabling precise horizontal and vertical adjustments of the telescope. Within the beacon receiver system, dedicated lens assemblies direct the beacon light onto a silicon (Si) Avalanche Photodiode (APD) to capture the low-speed data and a CMOS camera to provide real-time incident angle information. Together, these components provide a $\pm 6^\circ$ field-of-view (FoV) and an angular resolution of 30.2 $\mu\mathrm{rad}$[7]. After a threshold power is detected on the power meter, the algorithm performs an ultrafine scanning to optimize the fiber coupling efficiency. Overall, 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, forming a closed-loop feedback system that continuously ensures stable and robust connectivity.

Results

To comprehensively evaluate the performance of AraOptical system, six hours of data were recorded, including continuous power measurements and effective bit rates, using User Datagram Protocol (UDP) to avoid complete channel dropout caused by power fluctuations. Since the link was established, we have achieved a maximum effective bit rate of 2.62 Gbps in the *iPerf* test with UDP traffic using a single channel 10G transceiver. Fig. 3 presents one hour of simultaneous power recordings before and after LNA amplification at both Residence Hall and Agronomy Research Farm. The LNA operates in Automatic Power Control (APC) mode, and generates reception power above the receiver sensitivity and establishes the connectivity. However, a -27 dBm circulator leakage continuously mixes with the received signal, introducing power fluctuations in the receiver band, leading to a significant dynamic range increase of approximately 16 dB after amplification. One of the primary causes of channel dropout is the large dynamic range of signal fluctuations, which overwhelms the decision circuit in the SFP+ transceivers.

Two major causes of the link failure—misalignment and weather turbulence—are analyzed and illustrated. In Fig. 4, during the initial stage, misalignment results in relatively low reception power, significantly impacting the communication rate. However, after applying the alignment algorithm, the reception power improves considerably, demonstrating the algorithm's effectiveness in correcting misalignment and restoring optimal system alignment. These results not only validate the algorithm's efficacy but also highlight its crucial role in ensuring stable and reliable communication in AraOptical FSOC systems.

Futhermore, in Fig. 5, a 150-minute simultane-

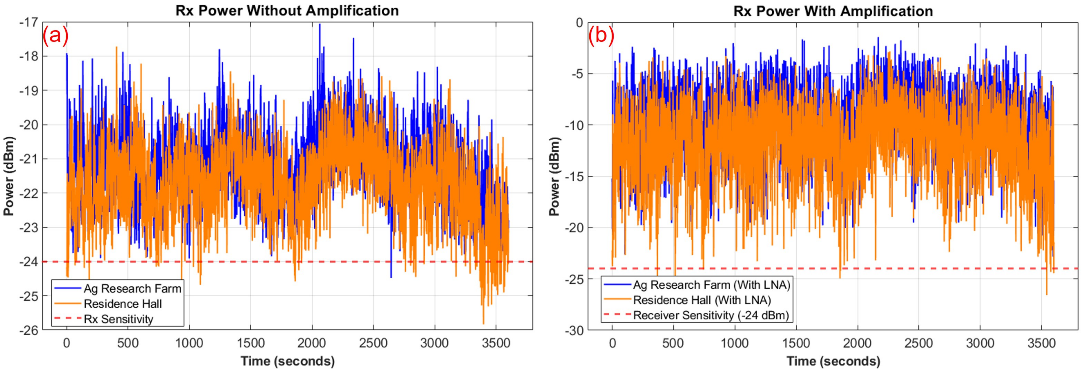

Fig. 3: Comparison of AraOptical reception power under different LNA configurations: (a) Without LNA amplification and (b) With LNA amplification

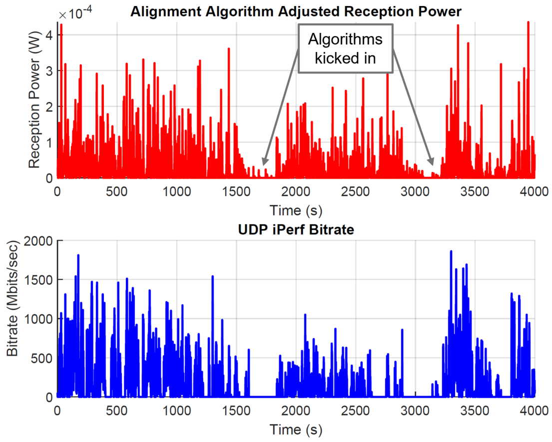

Fig. 4: AraOptical reception power after alignment algorithm correction.

ous power and bit rate recording was conducted, and the data is divided into one-minute blocks. To assess the strength of the prevailing turbulence, the refractive structure index C_n^2 is calculated for each block using the Log-Normal model and depicted[8]. From the results, we observe that although the reception power is amplified beyond the receiver sensitivity by the LNA, the increase in dynamic range causes an amplification of the weather turbulence effect. The C_n^2 value rises from a baseline level of $10^{-15}\,\mathrm{m}^{-2/3}$ to peak values of approximately $0.8 \times 10^{-15}\,\mathrm{m}^{-2/3}$ when LNA amplification is applied. During periods of high C_n^2, the UDP bit rate experiences severe degradation, dropping from an initial average of 600 Mbps to values as low as 0 Mbps, corresponding to turbulence spikes. Implementing an appropriate feedback system in LNA may help mitigate scintillation effects.

Beyond validating system functionality, the AraOptical platform serves as a valuable tool for understanding the operational boundaries of long-range FSOC under real-world rural conditions. The significant increase in dynamic range observed after LNA amplification, while beneficial to achieving sufficient power levels, exposes the receiver to increased sensitivity to scintillation. This dual effect highlights the importance of carefully balancing amplification gain and noise tolerance in FSOC front-end design. Our observations also suggest that introducing adaptive gain control or feedback-informed filtering mechanisms may improve robustness during turbulence spikes without compromising link availability. These findings underscore the value of real-time power monitoring and dynamic alignment control as essential components for practical FSOC deployment.

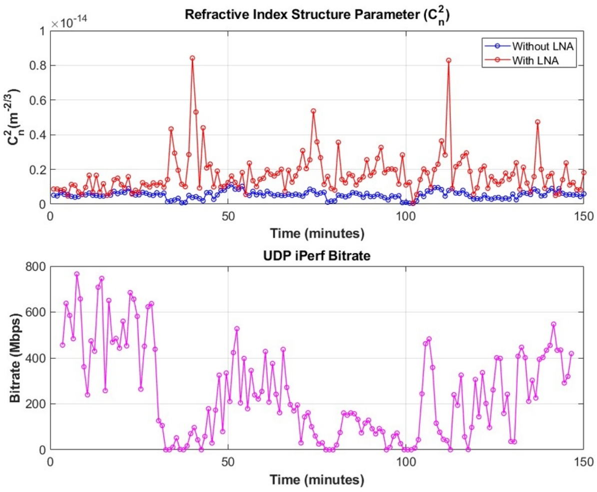

Fig. 5: Impact of atmospheric turbulence and LNA amplification on AraOptical link performance.

Conclusions

We demonstrated *AraOptical*, a 10.15 km long COTS-transceiver-integrated rural FSOC system, equipped with an effective auto alignment algorithm. First-hand field data is presented and the results revealed that while the LNA's amplification enhances reception beyond the receiver sensitivity of the transceivers, it also exacerbates scintillation effects, leading to potential channel dropouts. The FSOC system is integrated with ARA wireless living lab, and is publicly available to the scientific community for further experiments.

Acknowledgements

This work was supported by the U.S. National Science Foundation under grant number PAWR-5582469.

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