AraOptical System and Testbed for Long-Range, High-Capacity FSOC in Rural Wireless X-Haul Networks

MD NADIM, Iowa State University, USA
XUN LI, University of California, Irvine, USA
SALIL REDDY, The Ohio State University, USA
SARATH BABU, Iowa State University, USA
ARSALAN AHMAD, Iowa State University, USA
OZDAL BOYRAZ, University of California, Irvine, USA
DAJI QIAO, Iowa State University, USA
ANISH ARORA, The Ohio State University, USA
HONGWEI ZHANG, Iowa State University, USA

Long-range, high-capacity free-space optical communications (FSOC) is critical for terrestrial rural wireless x-haul and rural broadband in general. Existing terrestrial FSOC systems are however designed primarily for short-range communications. Long-range FSOC faces major challenges such as scintillation, weather, telescope misalignment, and sun noise, and there is a lack of FSOC systems and testbeds for investigating the feasibility and behavior of long-range, high-capacity terrestrial FSOC in realistic rural settings. To fill the gap, we design and implement AraOptical, a first-of-its-kind 10+ km FSOC x-haul system. We permanently deploy the AraOptical system and make it publicly available as the rural ARA testbed for empowering researchers worldwide to investigate long-range FSOC and wireless x-haul solutions. The AraOptical system features innovative designs for addressing key challenges of long-range FSOC. It effectively uses optimized COTS components such as feedback-controlled-low-noise-amplifiers and transceivers compatible with conventional routers, and it invents a novel multi-level auto-alignment algorithm tailored for the AraOptical system. The software framework of the AraOptical system features custom-designed APIs and facilitates the establishment of the ARA wireless living lab for real-world experimentation. Using the field-deployed ARA, we demonstrate, for the first time, the real-world feasibility of long-range terrestrial FSOC. AraOptical achieves a maximum throughput of 2.92 Gbps on a single channel, and, with 16 parallel channels, AraOptical is well-poised to scale to an aggregate capacity of 160 Gbps using 10G SFP+ transceivers, with potential for multi-Tbps capacity using 100G/400G coherent transceivers. We also quantitatively characterize the impact of scintillation and weather on long-range terrestrial FSOC, and we will publicly share the first-of-its-kind measurement data. The unique lessons learned from this pioneering real-world deployment of long-range FSOC systems will also facilitate future real-world studies and adoption.

CCS Concepts: • **Networks → Physical links**; **Wireless access points, base stations and infrastructure**; **Network experimentation**; **Network measurement**; • **Hardware → Wireless devices**.

Additional Key Words and Phrases: FSOC; long range; high-capacity; rural wireless x-haul; ARA

Authors' Contact Information: Md Nadim, nadim@iastate.edu, Iowa State University, Ames, Iowa, USA; Xun Li, xunl12@uci.edu, University of California, Irvine, California, USA; Salil Reddy, reddy.441@osu.edu, The Ohio State University, Columbus, Ohio, USA; Sarath Babu, sarath4@iastate.edu, Iowa State University, Ames, Iowa, USA; Arsalan Ahmad, aahmad@iastate.edu, Iowa State University, Ames, Iowa, USA; Ozdal Boyraz, oboyraz@uci.edu, University of California, Irvine, California, USA; Daji Qiao, daji@iastate.edu, Iowa State University, Ames, Iowa, USA; Anish Arora, arora.9@osu.edu, The Ohio State University, Columbus, Ohio, USA; Hongwei Zhang, hongwei@iastate.edu, Iowa State University, Ames, Iowa, USA.

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1 Introduction

Rural regions are major sources of food and energy for the whole society, thus rural prosperity is essential to societal well-being. As a foundation for rural economy and quality of life, rural broadband is a key driver [1, 38, 47]. Yet rural broadband remains a key challenge. For instance, 39% of the rural US and 52% of the global rural population lack broadband access, and most agriculture farms are not connected at all [38, 47]. To address the rural broadband gap, wireless networks are essential building blocks, as they incur lower cost than fiber networks in connecting regions of lower population density. In particular, given that rural towns are usually tens or even over 100 miles away from one another and that many rural towns and agriculture farms are far away from their nearest Internet backbone connection points [34], high-capacity, long-distance wireless x-haul networks serve as important *middle-mile* solutions that connect rural towns and agriculture farms with one another and with the Internet backbone [48]. While wireless x-haul systems have been used for a long time, the existing deployment of long-distance x-haul systems has been mostly limited to microwave bands (e.g., 6 GHz and 11 GHz). Due to the limited bandwidth available at the microwave bands, the communication capacity of these microwave x-haul systems tends to be limited (e.g., far less than 10 Gbps) and cannot meet the needs of broadband applications.

To address the challenge, there has been emerging interest in exploring free-space optical communications (FSOC) for high-capacity wireless x-haul networks. However, existing practice in long-range FSOC has been limited to inter-satellite data transfers, and terrestrial FSOC has been limited to short-range communications between close-by buildings. Long-range terrestrial FSOC is challenged by the stochastic inhomogeneity of FSOC channels and the complexity of robust FSOC systems. The inhomogeneity of the lower atmosphere creates local eddies and atmospheric turbulence that cause random changes in the received signal's amplitude and phase, leading to beam wandering (i.e., shift in beam centroid) and scintillation (which manifests as channel fading). The longer the free-space optical communication distance, the larger the beam wandering and scintillation. Despite numerous theoretical models of beam wandering and scintillation, real-world measurement studies to validate these theoretical findings remain lacking, so are field-deployable long-distance terrestrial FSOC systems that support field trials and experimental studies.

To fill the gaps in long-range FSOC studies and to enable long-range FSOC practice in high-capacity rural wireless x-hauls, we develop AraOptical, a first-of-its-kind field-deployable long-range FSOC system. Not only does AraOptical demonstrate strong potential for supporting long-range, high-capacity FSOC in practice, it also enables us to develop the AraOptical testbed, which in turn enables real-world characterization of the AraOptical systems behavior as well as the continuous evolution of the AraOptical system. As the first effort having realized field-deployed long-range, high-capacity terrestrial FSOC system and testbed, this work makes the following significant contributions:

(1) We design and implement AraOptical, a first-of-its-kind long-range, terrestrial FSOC system spanning 10.15 km in a real-world rural environment. The AraOptical system is built entirely using commercial-off-the-shelf (COTS) transceivers and components originally designed for fiber optic communications, demonstrating, for the first time, the feasibility of cost-effective, high-capacity FSOC deployment in rural settings.

(2) We develop a novel multi-level auto-alignment algorithm that leverages feedback-controlled low-noise-amplifiers (LNAs) and that integrates *coarse*, *fine*, and *ultra-fine* alignment mechanisms. This algorithm, to the best of our knowledge, is the first-of-its-kind in a field-deployable terrestrial FSOC system; it enables real-time compensation for mechanical vibrations, weather-induced scintillation, and beam wandering, thereby maintaining FSOC link stability.
(3) We integrate AraOptical into the ARA, creating the first open and field-deployed testbed for long-range terrestrial FSOC experimentation. The testbed serves as a unique, heterogeneous x-haul research platform that allows for end-to-end experimentation with FSOC and other wireless technologies under dynamic and realistic rural settings.
(4) We conduct the first real-world measurement study of long-range terrestrial FSOC, collecting outdoor data under diverse environmental conditions. The study offers novel empirical insight into the behavior of long-range FSOC, including the first-of-its-kind real-world characterization of scintillation and weather impact. AraOptical achieves a maximum throughput of 2.92 Gbps on a single channel, and, with 16 parallel channels, AraOptical is well-poised to scale to an aggregate capacity of 160 Gbps with SFP+ transceivers, with a potential for achieving multi-Tbps capacity using 100G/400G coherent transceivers.
(5) We document the lessons learned in the first-of-its-kind deployment and operation of long-range terrestrial FSOC systems. These lessons provide practical insight and guidance for FSOC systems design, deployment, and operation, bridging the gap between theoretical studies and field realities.

The remainder of the paper is organized as follows: Section 2 reviews related work across various dimensions of FSOC systems. Section 3 outlines the major challenges in designing such systems and describes how they are addressed in the development of AraOptical. Section 4 details the software framework, APIs, and enabled experimental studies, alongside the deployment of the AraOptical system as a testbed. Section 5 presents real-world measurement study using the AraOptical testbed, and Section 6 summarizes key lessons learned from the real-world deployment and operation of AraOptical. Finally, Section 7 concludes the paper.

2 Related Work

Real-world deployment and implementation of FSOC links remain highly challenging due to their susceptibility to weather-induced impairments, which can significantly affect link stability and robustness. To address such challenges, several research efforts have explored advanced mitigation techniques. In [35], a beam positioning system was designed to align the signal beam with the receiver's focal point, using control signals generated by a controller that combines statistical experimental design with an artificial neural network. However, the system was only validated in a simulation environment. Complementing this approach, Zou et al. [50] proposed a seamless rate adaptation FSOC scheme based on rate-compatible modulation, which adapts modulation levels under varying weather-induced channel conditions to maintain link robustness. This scheme was validated through simulations and tested over a 50 m indoor hallway FSOC link. In [21], Gupta et al. proposed a tracking and pointing algorithm for aligning FSO links using galvo mirrors, designed to support high-bandwidth virtual reality (VR) applications. Although effective in short-range indoor environments free from atmospheric turbulence, galvo mirrors inherently restrict the aperture size, resulting in increased beam divergence and a constrained power budget. These limitations render the approach impractical for long-range (10+ km) outdoor deployments, where continuous alignment is further complicated by scintillation, beam wander, and weather-induced fading. Beyond alignment strategies, the impact of transmit power on the outage probability of FSOC links was studied under clear weather and moderate rain conditions in [13]. Simulations showed that at shorter distances, increasing the receiver aperture diameter and transmit power can help reduce outages. Meanwhile, Curran et al. [17] introduced FSONet—a steerable FSO-based solution for picocell backhauls. While promising, its effectiveness is limited to short-range scenarios (100–200 m), in urban settings with relatively low bitrate requirements, and it has not yet been implemented in real-world deployment. Taking a more practical approach, an experimental field trial of a 1.8 km long uni-directional FSOC link with a temporary setup was presented in [18]. The system incorporated a turbulence mitigation technique with partial compensation for atmospheric turbulence and forward error correction optimization. However, the limited transmission distance makes the system inapplicable to long-range rural deployment. In recent years, considerable attention has also been given to hybrid FSOC and RF-THz systems those operating in the E-band/mmWave-bands [23, 28, 29, 41]. For instance, Lu et al. [30] proposed a fiber-FSOC system for 5G backhaul applications. While the FSOC link at 1.2 km length, the system primarily targeted urban scenarios and is not suitable for at-scale rural deployment.

Several industry-led initiatives have also focused on developing FSOC systems, specifically for enterprise networks and specialized defense applications. Companies such as Qinetiq [8], Cable-Free [4], fSONA [9], and Transcelestial [5] have primarily designed their commercial FSOC solutions for short-range point-to-point links, typically supporting distances up to 2 km with data rates up to 10 Gbps using on-off keying modulation [46]. For long-range communications, initiatives such as Google Taara [6] and Attochron [7] claimed operational ranges of up to 20 km; however, these systems are primarily deployed in tropical or subtropical regions where the weather conditions are more favorable than in rural regions with more harsh weather. A systematic characterization of the performance of long-range, high-capacity FSOC systems—specifically in terms of reliability and throughput under atmospheric disturbances—remains lacking [14, 19, 26, 39, 40]. While substantial efforts have been made to mitigate atmospheric turbulence [27, 36, 42, 49] and address challenges such as scintillation, beam wandering and wavefront distortion [35], enhancing the overall robustness of FSOC links remains an active area of research. Despite progress in improving specific performance aspects such as capacity, range, or alignment stability, most research and industrial efforts remain fragmented. A comprehensive solution that ensures robust, long-range, and high-throughput FSOC under real-world rural and harsh environmental conditions is still absent from the current literature and commercial offerings.

Among large-scale outdoor testbeds developed under the National Science Foundation's (NSF) Platforms for Advanced Wireless Research (PAWR) program [3], POWDER [16] focuses on advanced radio access network (RAN) and massive MIMO research. COSMOS [37], designed for ultra-high-bandwidth, low-latency wireless communications and edge cloud computing, incorporates a dark fiber-based optical x-haul solution [22]—a setup largely suitable only for short distances in urban areas. AERPAW [31] emphasized wireless communications with and for unmanned aerial vehicles. While these testbeds provide valuable infrastructures for cutting-edge wireless experimentation, their primary focus lies in urban-centric network paradigms and/or radio technologies, with limited attention to long-range, high-capacity, affordable wireless x-haul solutions for rural broadband and agriculture applications. In [24] and [48], we presented the vision, design, and implementation of the ARA wireless living lab, and emphasized the need for long-range, high-capacity wireless x-haul solutions. Building on that foundation, this paper extends the discussion by presenting the specific challenges, proposed solutions, and practical insights associated with the design and deployment of long-range, high-capacity FSOC systems through the introduction of AraOptical, an integral component of AraHaul [51]—ARA's wireless x-haul platform. As demands for high-capacity rural broadband grow, the lack of suitable long-range FSOC platforms remains a critical gap. AraOptical addresses this by serving both as a practical, field-deployable FSOC solution and as an open testbed, enabling real-world experimentation of next-generation rural wireless systems.

3 AraOptical System Design and Implementation

Designing long-range, high-capacity terrestrial FSOC systems remains challenging due to various factors, especially FSOC susceptibility to scintillation and beam wandering. In what follows, we elaborate on the overall AraOptical system architecture and how the challenges inherent in designing reliable FSOC systems are systematically addressed. The resulting AraOptical system represents a first-of-its-kind real-world deployment, demonstrating the feasibility of stable and resilient long-range FSOC operations under demanding field conditions.

System Architecture. To address the unique constraints of rural FSOC deployment, the AraOptical node is custom-designed and assembled in-house using a modular approach. The design leverages industry-grade, commercially available COTS components commonly used in advanced photonic and optical communication systems, ensuring cost-effectiveness, interoperability, and reconfigurability. Fig. 1 illustrates the architecture of an AraOptical node. To support long-distance, high-capacity FSOC, each AraOptical node is equipped with 16 commercially available 10G-Base-ZR Dense Wavelength Division Multiplexing (DWDM) Small Form-Factor Pluggable Plus (SFP+) transceivers operating across distinct wavelengths over single-mode-fiber (SMF). These transceivers support extended reach to ensure long-range x-haul transport use cases. The optical interfaces are managed through a Juniper ACX710 universal metro router [2], which acts as the core routing unit for optical traffic. The router interfaces directly with the DWDM module that multiplexes outbound and de-multiplexes inbound optical signals across multiple wavelengths, optimizing spectral efficiency and ensuring wavelength-selective transport with higher-layer packet-based services in the overall x-haul network. The AraOptical node shares the common WDM architecture used in fiber optic communications, except the telescopes that represent the transmission channel. Hence, the cost of the telescope unit in AraOptical replaces that of fiber and fiber deployment,

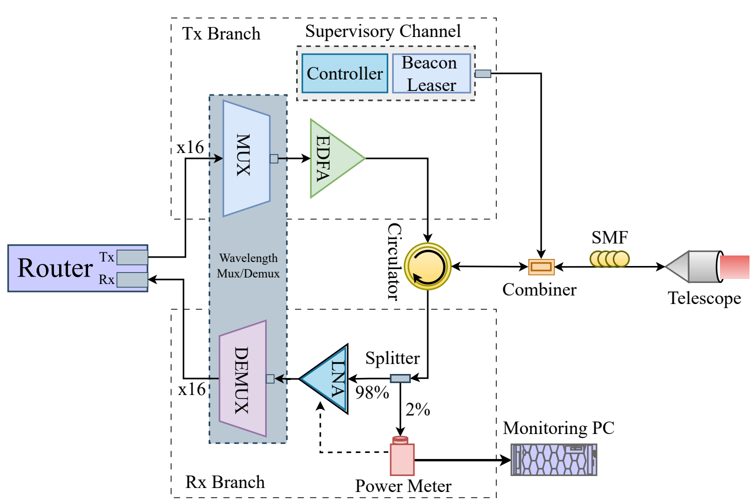

Fig. 1. Network architecture of AraOptical node showing integration between standard networking equipment (Router, EDFA, DWDM, and Optical Routers) and the optical telescope.

significantly reducing the x-haul cost as compared with wireline fiber deployment. To enhance the transmitted signal integrity, an Erbium-Doped Fiber Amplifier (EDFA) is integrated into the system, ensuring robust long-range terrestrial connectivity even under variable link conditions. The received signal (Rx) is first passed through a 98/2 optical splitter to ensure real-time monitoring and dynamic control of the optical link. While 2% of the optical power is directed to a high-sensitivity power meter for feedback to the alignment algorithm, the remaining 98% is routed to a Low-Noise pre-Amplifier (LNA) to boost the signal above the receiver sensitivity threshold. Operating in Automatic Power Control (APC) mode, the LNA amplifies the received signal based on the input power level. The amplified signal is then passed through the DWDM module, which selectively filters out transmission wavelengths, ensuring that only the desired received signal is forwarded to the routing interface. To ensure uninterrupted LNA operability, it is connected to the receiver branch of the optical circulator without any filtering, using the transmission (Tx) leakage power as a passive activation source. An Optical Collimator (CL) with a divergence angle of 35 µrad is used for over-the-air transmission. This ultra-narrow divergence angle significantly improves transmission efficiency by minimizing geometric loss. The key specifications of the AraOptical system are summarized in Table 1.

Table 1. AraOptical Key Specifications

Parameter	Specifications
Operational wavelength	1538.98 nm to 1563.86 nm
Operational frequency range	191.7 THz to 194.8 THz
Optical output power	33 dBm
Communication distance	≤ 20 km
Number of DWDM channels	16
Data Rate	≤160 Gbps

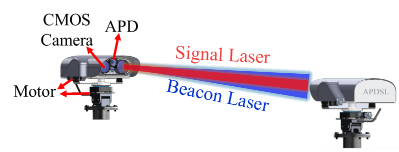

Fig. 2. Multi-level self-alignment beacon system

To mitigate reductions in reception power caused by incidence angle mismatches and beam walk-off, the architecture illustrated in Fig. 2 has been developed. A beacon laser operating at a wavelength of 980 nm, which primarily can be referred to as a management channel for performing alignment, is combined with the signal beam via a Wavelength Division Multiplexer (WDM) to avoid misalignment between them. Although both beams propagate along the same LOS path, the beacon beam is emitted with a significantly wider beamwidth to facilitate more accurate alignment during system operation. In addition, the self-alignment system employs two high-resolution motorized rotational stages, each capable of 0.23 µrad per micro-step, enabling fine-grained horizontal and vertical adjustments of the telescope. Within the beacon receiver subsystem, dedicated lens assemblies focus the incoming beacon light onto both a silicon (Si) Avalanche Photodiode (APD) and a Complementary Metal-Oxide-Semiconductor (CMOS) camera. The components of an AraOptical telescope and the complete AraOptical node are shown in Fig. 3 and Fig. 4, respectively.

Atmospheric Turbulence, Weather, and Scattering Effects. Atmospheric-turbulence-induced variations in the refractive index along an FSOC link lead to time-varying optical distortions in the optical beam, commonly referred to as *scintillation.* A critical challenge in establishing and maintaining FSOC links is mitigating the adverse effects of scintillation [11, 43] on the integrity and stability of the signal. To quantify the scintillation effect, the scintillation index [12], representing the normalized variance of received signal intensity, can be calculated as

$$\sigma_I^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1, \tag{1}$$

where $\langle I \rangle$ represents the ensemble average of the signal intensity and $\langle I^2 \rangle$ denotes the ensemble average of the squared signal intensity. The theoretical expression for weak turbulence conditions [12] is given by

$$\sigma_I^2 = 1.23\, C_n^2\, k^{7/6}\, L^{11/6}, \tag{2}$$

where C_n^2 is the refractive-index structure parameter that describes the strength of atmospheric turbulence, $k = 2\pi/\lambda$ is the optical wave number, with λ being the wavelength, and L is the length of the FSOC link. We see that the scintillation index increases with link length following a power law, even under weak turbulence conditions [44]. Under the same weather conditions, when the

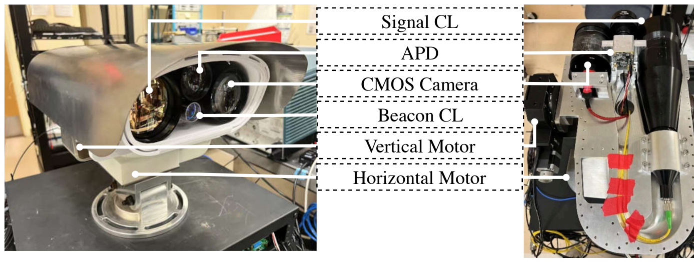

Fig. 3. Components of an AraOptical telescope

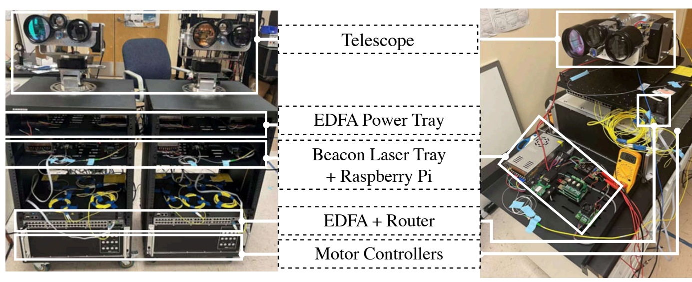

Fig. 4. Complete AraOptical node

link distance increases from 1 km to 10 km, the scintillation index grows by approximately a factor of 68. The lengths of typical rural FSOC links are 10 km or more [24]; these relatively long FSOC propagation paths, combined with humid and windy conditions, intensify the scintillation-induced fluctuations, which lead to large dynamic ranges of the received signals and are primary causes of channel dropout. Furthermore, adverse weather conditions such as haze, fog, rain, and snow exacerbate signal attenuation and increase scattering losses, potentially reducing the received signal power to be below the transceiver's sensitivity threshold and severely impacting the availability and reliability of rural FSOC.

To address the aforementioned challenges, we integrate feedback-controlled low-noise-amplifer (LNA) into the reception system design to ensure that even weakened signals remain above the receiver's sensitivity threshold, thereby supporting continuous communications. The feedback system in the LNA has 50 ms time constant and used to set the output power to a constant value. With such time constant we can correct fluctuations up to 20 Hz and provide constant output power to the receiver. Without the feedback system and dynamic control, the LNA amplifies the received signal, it simultaneously increases the amplitude of power fluctuations, leading to an expanded dynamic range that may overwhelm the transceivers' decision circuits, eventually causing a channel dropout. Once the LNA compensates the power fluctuations due to scintillations, the concern shifts from power fluctuation to optical signal-to-noise ratio (OSNR). Specifically, when the input signal is weak, the amplifier introduces a significant amount of amplified spontaneous emission (ASE) noise, which degrades OSNR and compromises the integrity of optical communication links. Based on input power values, we identify 0 dBm output setting provide high OSNR for maximum throughput.

Mechanical Stability. FSOC links require highly stable platforms to ensure robust, reliable, and consistent communications. Otherwise, minor vibrations caused by wind, building oscillations, or other external disturbances can destabilize the platforms, leading to misalignment and thus significant signal loss [15, 17]. Considering a Gaussian beam propagating in free space, the intensity distribution of the beam [10] as a function of radial distance r at a propagation distance z is given by

$$I(r,z) = I_0 \exp\left(-\frac{2r^2}{w(z)^2}\right), \tag{3}$$

where I_0 is the peak intensity at the beam center, and $w(z)$ is the beam radius at distance z. For kilometer-scale FSOC applications, where propagation distance is much greater than beam waist, $w(z)$ can be approximated using the divergence angle θ_0 as

$$w(z) = \theta_0 z. \tag{4}$$

If the system experiences angular misalignment or vibration with an angle θ, the Gaussian beam will undergo a lateral displacement or walk-off, Δr, at the receiving plane located at distance L, expressed as

$$\Delta r = L \cdot \theta. \tag{5}$$

Thus,

$$I(\theta) = I_0 \exp\left(-\frac{2\theta^2}{\theta_0^2}\right) \tag{6}$$

demonstrates fiber coupling efficiency, which refers to the alignment and connection of a light beam from an optical fiber to the FSOC system; it decreases rapidly with increasing angular misalignment in relation to the intensity of the optical beam divergence angle, $I(\theta)$, as it follows a Gaussian profile centered at the zero angle. For instance, in a typical rural deployment with a link length of 10 km or more, a 20 µrad vibration-induced angle deviation in the signal beam with a 35 µrad divergence angle results in an intensity fluctuation of approximately 47.95%. An FSOC system, deployed on a high infrastructure or monopole tower, is prone to frequent movement due to environmental factors, increasing the risk of FSOC link misalignment. Moreover, since stepper motors are commonly involved in the alignment mechanism of FSOC systems, backlash and repeatability errors must also be considered as contributing factors to misalignment. An auto-alignment restoration process is a crucial design consideration to counteract misalignment caused by mechanical instability.

Considering the extremely narrow beams and long distance of rural FSOC links (for example, 70 cm beamwidth after 10.15 km in our system), precise alignment is a challenge. To address this, FSOC telescopes are mechanically mounted and pre-aligned within the scanning range of the motors (e.g.,±90° horizontally and ±6° vertically). This setup enables automated scanning and alignment algorithms to accurately determine the direction of the remote end, facilitating the establishment and maintenance of the initial handshake. Therefore, the flexibility of the telescope's physical rotation and tilting range is a crucial consideration in the system design.

AraOptical Auto-Alignment Algorithm. AraOptical is integrated with multi-level auto-alignment algorithms to accurately align the position of the FSOC telescopes to consistently maintain the link under conditions such as atmospheric turbulence (e.g., different weather conditions) and structural disturbances (e.g., physical vibration, scintillation, and beam wandering). Unlike satellite-based FSOC [20, 25, 32], terrestrial FSOC systems are far more vulnerable to fading and scintillation effects caused by near-ground atmospheric turbulence. In addition, the use of commercially available integrated transceivers limits receiver sensitivity, since these components cannot be modified beyond vendor-defined specifications. Transmit power is also restricted by eye-safety regulations, further constraining the link budget and posing challenges for long-range terrestrial FSOC deployments.

The alignment algorithm operates at three levels: *coarse alignment*, *fine alignment*, and *ultra-fine alignment*. The algorithm leverages inputs from the APD, CMOS camera, and power meter to adjust the telescope orientation via two axes of motorized stages, i.e., vertical and horizontal movements, to compensate for any misalignment. Once we have the handshake signal from the initial alignment stage, the *coarse* alignment stage starts, where we try to maximize the APD voltage. The APD is enabled with a wide detection area of 100 mm^2 and is placed behind a 50 mm double-convex lens, which provides the most *coarse* alignment with the largest angle of view up to ±6.5°. Upon successful detection of the handshake messages, the algorithm initiates the comparison process for APD voltage maximization, thereby triggering the commencement of the *fine* alignment phase. The *fine* alignment is then accomplished by a 24 mm^2 CMOS camera with a pixel size of 3.45 µm × 3.45 µm and a 75 mm aspheric lens that detects the pixel-to-pixel movement of the focused beacon beam when the incidence angle deviates, yielding a 30 µrad angular resolution. Once the spot is localized on the CMOS camera, the *ultra-fine* alignment is conducted based on the monitored reception power through the optical signal collimator to optimize the fiber coupling efficiency. The different levels of alignment algorithm are performed sequentially with various step sizes. Fig. 5 illustrates the step-by-step procedures for performing *coarse, fine,* and *ultra-fine* alignments using the multi-level auto-alignment algorithm.

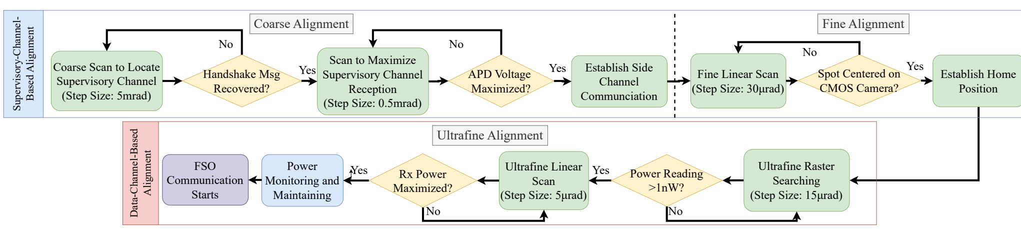

Fig. 5. AraOptical control flowchart of multi-level auto-alignment algorithms

The beacon system of AraOptical also includes a side communication channel, which facilitates the purpose of initial handshaking and the transmission of critical alignment information to the remote end. The beacon laser is modulated using the On-Off Keying (OOK) modulation coding scheme, operating at a low data rate of 1 Mbps to serve as a management channel. Upon receiving the alignment information on the APD at the receiver end, it is directly sent to an analog-to-digital converter (ADC) linked to the onboard computer. Subsequently, the onboard computer handles the task of recovering the clock and data in the digital domain and makes further decisions based on the received information.

To ensure effective functionality of the auto-alignment algorithm, a highly sensitive power meter is installed at the AraOptical node. An optical power splitter module is used to measure the Rx power level, which directly informs the link auto-alignment process. A dedicated Dell Optiplex computer controls and monitors the power meter and also serves as initial storage for power measurement data. Typically, the built-in power meter of the transceiver has a minimum detectable power of 0.1 µW with an approximate refresh rate of 2 seconds. To overcome this limitation, this highly sensitive external power meter was integrated into the AraOptical system, capable of detecting power levels down to the picowatt range with real-time response capabilities.

Sun Noise. In FSOC deployments, sun noise must be considered as a broad-spectrum noise source, especially when free-space optical detectors are used. The Sun's broad spectral emission can interfere with optical signal reception, reducing the OSNR and potentially degrading performance. Therefore, mitigating solar interference by filtering sun noise is a critical design consideration for optimizing system performance. To mitigate sun noise interference—one of the key environmental challenges—for the APD detector and CMOS camera, narrow band-pass optical filters are integrated into the AraOptical design. In the signal branch, although minimal sun noise is coupled to the collimator due to its limited acceptance angle, the signal undergoes additional filtering through

DWDM, further reducing the impact of solar interference. Moreover, analyzing the sun noise captured by the CMOS camera enables a precise initial alignment.

Furthermore, during the system design, losses associated with individual components were systematically evaluated and quantified to optimize overall system performance. The analysis revealed that the fiber coupling loss alone accounts for approximately 6 dB, while the circulator, combiner, and splitter introduced an additional 4 dB loss at the Tx and Rx ends. Therefore, the total insertion loss attributed to telescopes and their associated components could reach 14.3 dB. An additional 16 dB loss was estimated as geometric loss within the free space channel, primarily caused by beam divergence [45]. To compensate for these losses and ensure sufficient signal strength at the receiver, the EDFA was used to increase the transmission power to 2 W prior to initiating the actual free-space transmission.

4 AraOptical Testbed: Real-World Deployment, Software, API, and Experimentation

AraOptical Testbed Deployment and Integration. To enable real-world measurement study of long-range FSOC, we integrate the AraOptical system into the ARA, as illustrated in Fig. 6. ARA is an at-scale wireless living lab for advanced wireless research deployed in rural farmland. It consists of cellular base stations (BSs) and user equipment (UEs), which researchers can reserve to carry out experiments in advanced wireless systems. Unlike most cellular systems in urban/suburban settings, BSs in the ARA are not necessarily connected via fiber to reflect the rural reality, and many BSs use wireless x-haul to connect to one another and to the core network and the Internet. As the first-of-its-kind rural FSOC system, AraOptical nodes are deployed at two ARA base station sites, Agronomy Farm (mounted on a 70 ft monopole wireless tower) and Wilson Hall (mounted on a

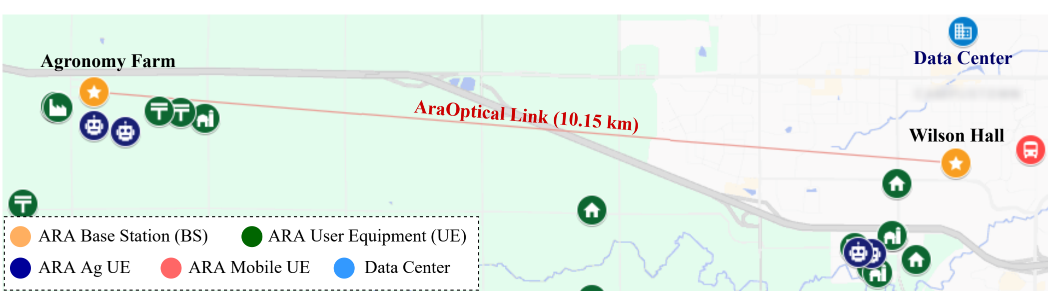

Fig. 6. AraOptical testbed deployment map in the ARA

(a) Agronomy Farm **(b)** Wilson Hall

Fig. 7. Deployment sites of the AraOptical FSOC system

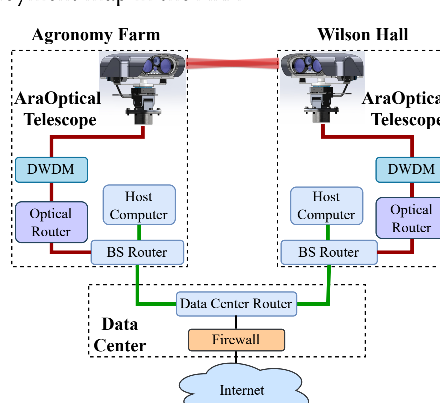

Fig. 8. Field-deployed AraOptical system architecture

130 ft tall building rooftop using a sturdy steel pipe), to form a long-range FSOC link between them. A snapshot of the AraOptical node deployment is shown in Fig. 7.[1] The network architecture of the AraOptical integration in ARA is depicted in Fig. 8. At each end of the FSOC link, an AraOptical node is interfaced with a Juniper ACX710 router, which functions as the optical router within the FSOC setup and is directly connected to a Juniper ACX710 BS router to facilitate AraOptical management, remote accessibility, Precision Time Protocol (PTP) synchronization [33], and seamless data-traffic forwarding across the ARA and to the Internet. The BS router at each BS site serves as a gateway for the AraOptical system, making it accessible for experimental studies through an AraOptical host computer, which connects to the BS router via fiber through SFP+ multi-mode transceivers.

AraOptical Software and API Framework. The AraOptical software framework is designed to manage and coordinate all system components to ensure robust link stability, operational reliability, and support for experimental research. Fig. 9 provides an overview of the AraOptical software architecture. Designing a unified software framework for AraOptical poses significant challenges due to the system's intricate architecture, which comprises a set of tightly coupled components that require precise coordination for control, monitoring, and diagnostics, and the need for fast dynamic control of the link. To manage this complexity, we design and develop the AraOptical API framework, a unified, extensible interface that exposes control and measurement capabilities via RESTful APIs. The APIs enable convenient access to critical telemetry and control knobs provided by system components, ranging from EDFA controllers and optical routers to power meters and signal amplifiers, that are essential for maintaining link stability and system performance. As shown in Fig. 9 and summarized in Table 2, the framework enables seamless integration with the AraOptical subsystems, and supports interaction through both a custom command-line interface (AraOptical CLI) and programmatically via user-defined clients. The development of our API framework addresses various challenges such as abstracting heterogeneous vendor protocols and ensuring robust access control.

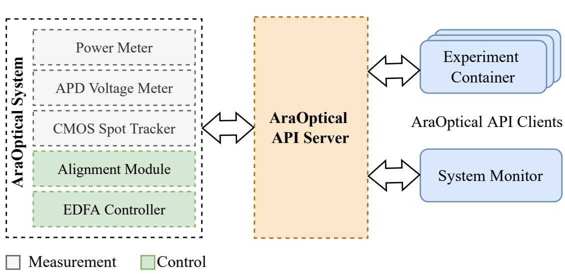

Fig. 9. AraOptical software overview

Table 2. AraOptical API Endpoints

API Type	API Endpoint	Description
Management	/enable	Enable router interface
	/disable	Disable router interface
	/edfa/workmode	Set EDFA work mode
	/edfa/activate	Activate EDFA
	/edfa/deactivate	Deactivate EDFA
Measurement	/status	Get interface diagnostics
	/pm/status	Get power meter reading
	/edfa/status	Get EDFA status

The AraOptical API framework is central to transforming AraOptical from a static optical link into a dynamic and reconfigurable experimentation platform. For instance, the `/status` API provides both the received power level and laser output power—key metrics for assessing FSOC link stability and monitoring power fluctuations at the source, respectively. The API framework allows researchers to conduct advanced studies such as: (1) correlating power meter readings with environmental data to understand link behavior under varying weather conditions, and dynamically tuning system parameters for improved reliability and throughput; (2) implementing selective channel activation or slicing to adaptively manage capacity based on real-time performance demands; and (3) evaluating the effectiveness of auto-alignment algorithms under fluctuating conditions such as beam scintillation and structural vibration, enabling iterative improvements.

[1]Note that the ARA co-locates microwave and mmWave x-haul radios (i.e., AraHaul-micro and AraHaul-mm radios) with the AraOptical system, enabling multi-band wireless x-haul system for robustness and capacity [51]

Furthermore, by supporting open API access, the framework ensures researchers can develop custom clients and deploy automated experiments.

Experimentation Enabled by AraOptical Testbed. Integrating AraOptical into ARA involves interfacing the former with the latter's centralized controller, as shown in Fig. 10. ARA leverages an OpenStack-based orchestration platform to manage the experiment lifecycle for researchers. Through its web-based interface, ARA Portal, users can log in and reserve experimental resources—the AraOptical host computers that interface with their FSOC modules and operate the AraOptical API servers. To enable reproducible experimentation, ARA employs container-based resource allocation. Users launch Docker containers on their reserved AraOptical host computers that serve as the execution environment for experiments. Within these containers, users can utilize the AraOptical-CLI or write custom Python programs that invoke the APIs to configure and control the FSOC link. These API interactions allow real-time monitoring and control of AraOptical parameters, enabling experiments involving alignment, channel configuration, link monitoring, or delay and throughput measurement under varying environmental conditions. Upon completion of experiments, users can terminate their containers and release the resources back to the resource pool. In short, the integration of AraOptical API framework into ARA establishes the first-of-its-kind, high-capacity, long-range FSOC testbed, empowering the research community to explore, prototype, and evaluate FSOC x-haul technologies in real-world rural settings.

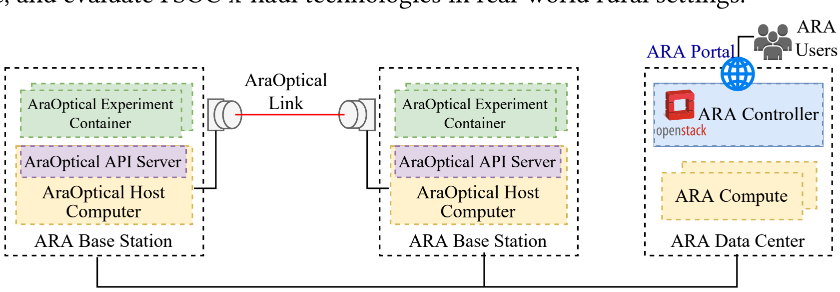

Fig. 10. ARA: architectural overview

Moving forward, the AraOptical system offers rich capabilities for advancing long-range FSOC-based x-haul transport in 5G and beyond. As a distinctive component of ARA, it enables researchers to explore how such systems can deliver high-throughput broadband in rural areas through fully-programmable, heterogeneous wireless architectures. Within the broader vision, AraOptical also provides a compelling foundation for experimentation in Open RAN systems. Specifically, it can be configured to function as fronthaul, midhaul, or backhaul segments, allowing researchers to evaluate FSOC performance across different layers of Open RAN infrastructure. With support for 16 channels, the system allows experimentation on channel-based transport slicing, dynamic resource allocation, service differentiation under multi-tenant settings. Furthermore, AraOptical facilitates the assessment of whether FSOC links can meet the stringent latency, bandwidth, and reliability requirements of Open RAN x-haul under real-world deployment conditions, thereby advancing the development of resilient, future-ready network architectures.

5 Real-World Measurement Characterization of AraOptical System

The AraOptical system represents the first real-world deployment and operational validation of long-range terrestrial FSOC, specifically engineered for rural environments. Through extensive first-of-its-kind field measurements in the AraOptical testbed, we uncover critical insights into link stability, atmospheric scintillation, and impact of alignment algorithms. Our results demonstrate a peak throughput of 2.92 Gbps on a single channel, validating system feasibility and establishing a clear path toward aggregating 16 DWDM 10 Gbps channels to scale up the capacity to 160 Gbps, and further higher capacity with state-of-the-art coherent transceivers. These empirical findings confirm AraOptical's potential as a practical and scalable FSOC solution, grounded in real-world performance data.

Impact of LNA Integration. The 10.15 km AraOptical link in the AraOptical testbed experiences significant optical power attenuation due to atmospheric turbulence, structural disturbance, weather-induced impairments, and geometric and coupling losses. As illustrated in Fig. 11, the received power without amplification fluctuates between -18 dBm and below -35 dBm at both ends, often approaching or falling below the receiver sensitivity threshold of -24 dBm. Such deep fades jeopardize link stability, resulting in frequent channel dropouts and degraded performance. To counteract this, we integrate an LNA with feedback control output, raising the signal floor and reduce the channel dropout rate. The AraOptical link has been tested with different output settings from 0 dBm to 10 dBm. We observe that spontaneous emission noise becomes dominant at higher gain values and destabilize the link despite high signal floor and average power values. Our empirical findings identify 0 dBm output as the optimal setting achieving a balance between signal amplification and noise suppression. The maximum signal power rises up to -3.5 dBm. With amplification, the median received power improves significantly to -11.5 dBm at the Wilson Hall (nearly 17× gain) and -9.87 dBm at the Agronomy Farm (nearly 26× gain), consistently keeping the signal above sensitivity threshold. In fact, as demonstrated in Fig. 11, the green dashed line marks the receiver sensitivity threshold, against which the amplified signal levels show a clear improvement margin, confirming the role of the LNA in stabilizing and maintaining a robust AraOptical link under varying conditions.

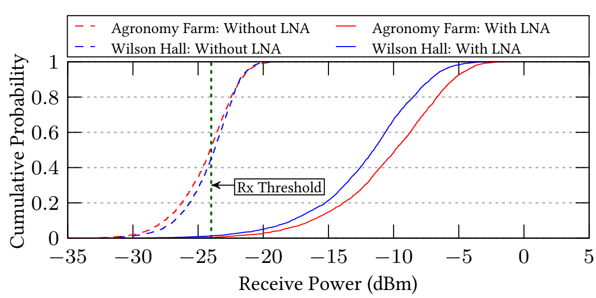

Fig. 11. CDF of AraOptical reception power over time

Scintillation and Weather Impact. We conducted the first comprehensive measurement campaign on the terrestrial long-range FSOC network under varying environmental conditions, generating a unique dataset that provides unprecedented insight into the degradation phenomena of network performance in real-world environments. Our measurement study on the AraOptical link under varying rainfall conditions reveals interesting insights to evaluate its behavior under weather-induced optical impairments. Fig. 12 highlights rain-induced impacts on the received signal, with the CMOS camera capturing beam spot distortions as a visual proxy of the signal degradation. As rain intensity increases, the received beam becomes increasingly distorted. The top-right panel of Fig. 12 presents a comparison of the average pixel density (ranging from 0 to 255) under different rain rates. In clear conditions (left of the panel), the beam appears bright and sharply defined; under moderate rainfall (0.12 inches/hour), shown as the middle of the panel, the beam becomes visibly degraded; and during heaving rain (0.75 inches/hour), shown as the right-most figure in the panel, the beam becomes nearly undetectable. These results indicate that AraOptical exhibits reasonable robustness under light to moderate precipitation, with substantial degradation observed primarily during severe weather conditions.

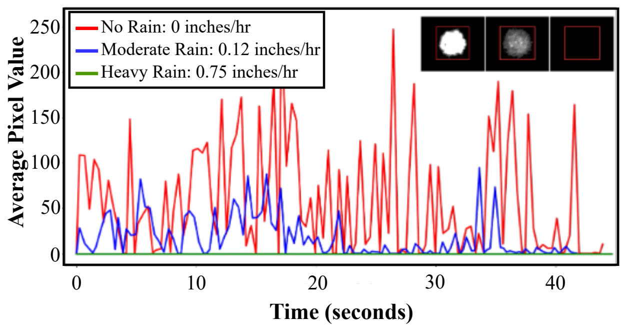

Fig. 12. AraOptical CMOS camera pixel density under different rain rates

As a major contributor to power fluctuations and potential channel dropout, the scintillation effect is thoroughly analyzed in Fig. 13. A 150-minute continuous recording of received power and bitrate was conducted simultaneously and segmented into one-minute intervals. Using the Log-Normal model, both the Rytov variance σ_I^2 (i.e., the scintillation index) and the refractive structure index C_n^2 are calculated for each interval to assess turbulence strength. The results reveal that while the LNA effectively amplifies the received signal beyond the receiver sensitivity threshold, it also increases the dynamic range of power fluctuations, thereby amplifying the scintillation index. This occurs because the LNA proportionally amplifies both the optical signal and the turbulence-induced intensity variations. Channel dropout—defined as intervals with mean bitrate below 100 Mbps—correlates strongly with peaks in scintillation. Nonetheless, these insights offer a valuable path forward: by integrating adaptive gain control with LNA or variable optical attenuators in the receive chain, FSOC systems can be further fortified against turbulence-induced degradations, making high-speed, long-range optical communication more resilient and robust under adverse conditions.

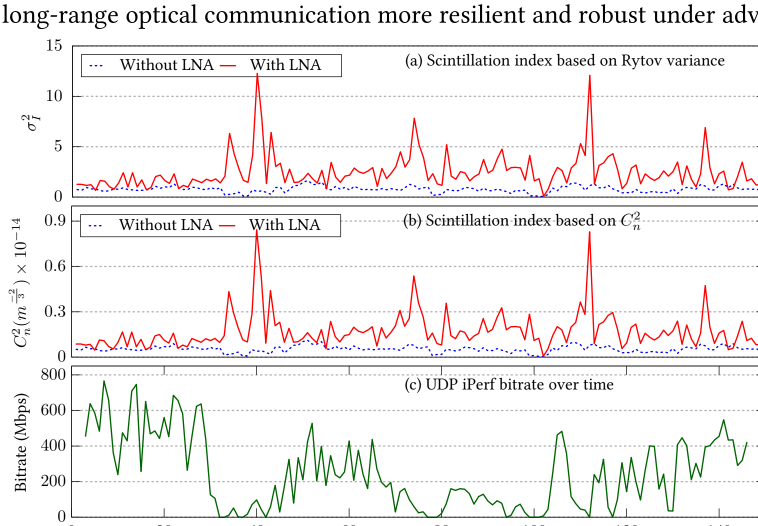

Fig. 13. AraOptical scintillation index and UDP iPerf bitrate over time

Effectiveness of Auto-Alignment Algorithm. Fig. 14 clearly illustrates the substantial effectiveness of the proposed alignment algorithm in optimizing optical received power in the FSOC system. The figure presents a comparative analysis of Rx power levels before and after the algorithm's application. In the initial stage, due to misalignment, the Rx power is significantly degraded, directly affecting achievable communication rate. Upon activation of the alignment algorithm, a marked improvement in Rx power is observed, demonstrating that the algorithm successfully compensates for the initial misalignment and restores the system to optimal alignment state. This result not only validates the algorithm's functional accuracy but also underscores its critical role in sustaining efficient and stable communication over FSOC links in the presence of environmental disturbances, thereby ensuring better link quality, reduced signal attenuation, and enhanced reliability. Therefore, the algorithm holds significant practical value in ensuring the performance and robustness of FSOC systems. As discussed in Section 3, the alignment algorithm is designed to maintain robust link performance under challenging outdoor conditions by addressing both rapid and gradual disturbances. High-frequency vibrations and weather-induced turbulence can distort the optical beam, causing significant instantaneous power fluctuations. In contrast, slower motor drift presents a persistent and long-term issue that can gradually degrade alignment over the course of an hour. To mitigate this effect, the algorithm employs averaged power measurements (10 acquisitions over 2 seconds) rather than relying on instantaneous readings, which may momentarily drop to zero due to scintillation or weather-induced fading. This approach effectively compensates for motor drift and ensures stable, long-term alignment.

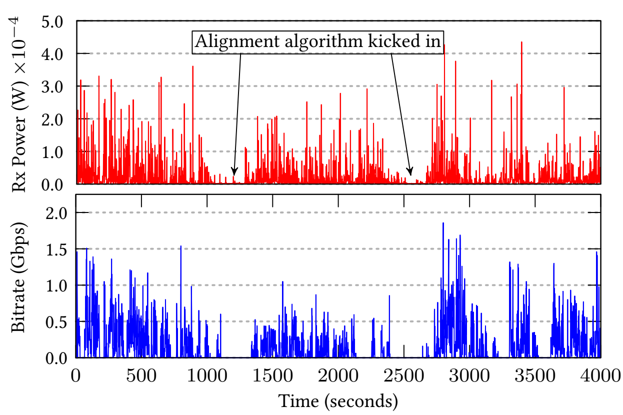

Fig. 14. Impact of alignment on AraOptical reception power

AraOptical Network Capacity & Scaling Potential. Based on the measured data illustrated in Fig. 15, we observed a peak throughput of 2.92 Gbps on a single 10 Gbps channel, corresponding to a received optical power of −3.3 dBm, under stable link conditions ensured by effective operation of auto-alignment mechanisms. This represents the first demonstration of a multi-Gbps optical wireless transport network over 10+ km terrestrial FSOC link under real-world rural conditions with associated mechanical and environmental challenges. The AraOptical architecture is designed to support 16 independent DWDM channels, each provisioned for 10 Gbps capacity using the COTS 10G SFP+ transceivers, enabling a theoretical aggregate throughput of 160 Gbps. Furthermore, the AraOptical architecture supports integration of higher-capacity coherent transceivers. Commercial coherent transceivers are available in 100 Gbps and 400 Gbps QSFP form factors, which could enable substantially higher aggregate capacities. With 100 Gbps and 400 Gbps coherent transceivers across 16 channels, the system could theoretically support 1.6 Tbps and 6.4 Tbps aggregate capacity, respectively. However, achieving these higher capacities requires addressing additional technical challenges including power budget optimization and enhanced environmental compensation mechanisms.

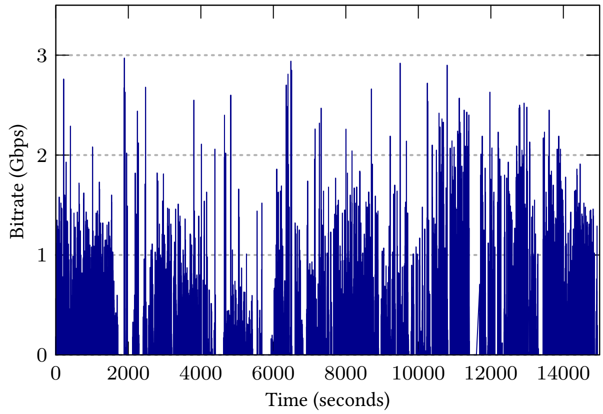

Fig. 15. AraOptical throughput

The current performance, representing 30% of the nominal 10 Gbps channel capacity, is primarily constrained by the sensitivity limitations inherent to COTS transceivers. Our single-channel results provide a promising foundation for scaling toward the system's full capacity through the integration of coherent transceivers with higher sensitivity and dynamic range, advanced LNAs equipped with adaptive gain control, and more responsive auto-alignment algorithm. These capacity enhancement investigations represent independent research directions worthy of dedicated studies, as they involve complex interactions between optical physics, network protocols, and environmental adaptation that require extensive systematic evaluation beyond the scope of this paper which establishes an initial feasibility. The AraOptical system and testbed resulting from this current work will enable such interesting and impactful future studies.

6 Lessons from Real-World Deployment and Operation of AraOptical System

Real-world deployment of long-range FSOC systems in rural settings brings with it a distinct set of engineering, environmental, and logistical challenges, which differ substantively from those in the controlled environments of labs and simulations. In what follows, we share the lessons learned in the first-of-its-kind deployment of the AraOptical system, towards offering insights into real-world deployment and operation of long-range FSOC systems.

Fig. 16. LOS testing with a red light source and astronomical telescope at Wilson Hall

Ensuring Line-of-Sight (LOS). One of the most critical challenges in deploying long-range AraOptical was ensuring Line-of-Sight (LOS) between the two end-points of an FSOC link. Aligning the 10.15 km optical path between two sites of the ARA proved far more intricate than expected. Initial coarse alignment was attempted using riflescopes mounted on the AraOptical telescopes, tracked via Bluetooth-enabled devices. Then, we have employed an astronomical telescope (Celestron StarSense Explorer), as shown in Fig. 16, for a further inspection and reveal potential blockage that cannot be achieved by riflescopes. Combined with blinking read beacons, astronomical telescope was effective in confirming line of sight. However, it was not sufficient to establish side channel communications. Eventually, we found out that the imaging through the leakage sun noise in CMOS camera was more effective during the day time to locate nodes. It was only after analyzing sun noise images from the CMOS camera and after careful realignment, the link was finally established, marking a key breakthrough in bringing AraOptical operational.

Transceiver Sensitivity. Ensuring reliable operation over a long-distance FSOC link depends critically on transceiver sensitivity. We began our deployment with 10 Gbps SFP+ transceivers rated for a receive sensitivity of -24 dBm. Even though we established the link, it remained unstable despite repeated attempts, prompting us to explore 1 Gbps transceivers that promised better sensitivity of -28 dBm. Surprisingly, link establishment still remained elusive even with the supposedly more sensitive transceivers. This led us to revert to the 10 Gbps transceivers and investigate more deeply. Using a high-sensitivity optical power meter in the loop, we discovered that the received signal was weaker than the -24 dBm threshold. To address this, we introduced a low-noise amplifier before the transceiver to boost the signal strength, enabling reliable detection. In short, the combination of the 10 Gbps transceiver, LNA, and alignment algorithm significantly improved the link robustness. These insights have motivated us to revisit the 1 Gpbs transceivers with LNAs in the loop and to explore hybrid setups involving both transceiver types to better understand the trade-offs between sensitivity, data rate, and system resilience. It is also important to note that the relatively low 50 ms feedback time constant of LNA may not overcome fast fluctuations. This motivates design of new LNAs with faster time constant to perfectly compensate power fluctuations. To achieve this, we determine that we should use LNA with below 1 ms time constant that can be achieved by semiconductor amplifiers rather than conventional rare-earth doped amplifiers, such as EDFA.

Transceiver Synchronization Dynamics. A persistent challenge in maintaining a robust AraOptical link has been the loss of synchronization between the transceiver and the router interface, often triggered by fluctuations in received optical power. Such fluctuations—caused by environmental factors such as turbulence and minor misalignment—can occasionally force the transceiver to lose its lock with the router. When the received signal power deviates significantly from the expected threshold, the transceiver can struggle to automatically renegotiate and re-establish synchronization. In such cases, a remote reboot of the interfaces (via software commands executed through an automated script) was necessary to restore the link. Notably, even with acceptable power levels, large variations (e.g., from -24 dBm to -3 dBm) can degrade the SNR (as shown in a continuous measurement as illustrated in Fig. 17), challenge the receiver's automatic gain control, and impact decoding accuracy. Our alignment algorithm plays a crucial role in mitigating such power fluctuations; however, the underlying behavior of COTS transceivers under these dynamics warrants further investigation. In addition, this highlights the need for a watchdog script that can automatically detect synchronization loss and autonomously restart the interface. Despite these hurdles, the system showed promising resilience and performance during stable conditions as observed in Fig. 17.

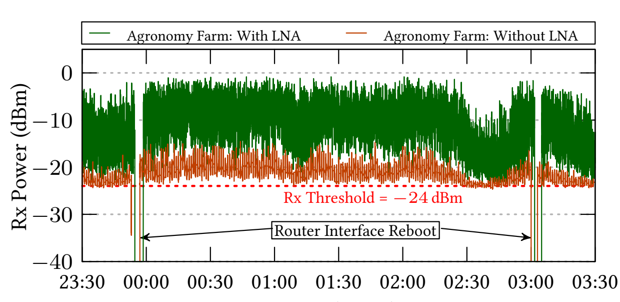

Fig. 17. AraOptical reception power over time

Harsh Weather Conditions. Operating AraOptical in extreme winter conditions revealed significant mechanical and optical challenges. Prolonged exposure to subzero temperatures caused the outer housings of both vertical and horizontal motor assemblies to freeze, making fine alignment infeasible during critical periods. Furthermore, ice accumulation on the telescope's front aperture degrades signal quality and interrupted operations, despite the presence of an anti-fog glass and fan system intended to prevent dust and particulate buildup. These challenges underscore the importance of designing FSOC systems that are not only optically precise but also environmentally adaptive. To this end, we are exploring the integration of a low-power internal heating element within the telescope enclosure to prevent freezing of critical components. We expect the intervention to enhance operational continuity during cold-weather deployments, thus helping enable the deployment of FSOC links in diverse and demanding rural environments.

Unresponsive Motor Controller. During alignment operations, one persistent challenge was the intermittent unresponsiveness of the motor controller units, which halted the telescope movement and required manual power cycling to restore functionality. Such interruptions not only delayed the alignment process but also limited real-time system adjustments—a key need for ARA. To overcome this issue, we integrated smart power distribution units (PDUs) into the AraOptical cabinets and networked them with the ARA management interface, enabling remote power control and rebooting capabilities and eliminating on-site interventions. The solution not only improved operational reliability but also reinforced the importance of remote management systems in future FSOC deployments.

7 Concluding Remarks

Having successfully developed, deployed, and operated the long-range FSOC system AraOptical in real-world rural settings, this work represents a key milestone in long-range terrestrial FSOC and wireless x-haul study. AraOptical has demonstrated the real-world feasibility of long-range, high-capacity FSOC, and it has helped made the first-step towards real-world adoption of long-range FSOC. The first-of-its-kind real-world characterization of the AraOptical systems behavior helps identify important next steps in FSOC systems research, for instance, adaptive LNA gain control, use of coherent transceivers, and leveraging spatial diversity to mitigate scintillation impact through multi-input-multi-output designs. The real-world deployment of the AraOptical testbed will enable such systems research and real-world pilots.

Acknowledgments

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