AraHaul: Multi-Modal Wireless X-Haul Living Lab for Long-Distance, High-Capacity Communications

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***Abstract*—For rural regions where towns and agricultural farms lack affordable broadband access, long-distance, high-capacity wireless x-haul communications to the nearest Internet fiber backbones are critical. Despite extensive experimental research in advanced wireless systems, there remains a lack of systematic studies on rural wireless x-haul systems as well as a lack of at-scale, real-world testbeds that support such studies. To redress these gaps, we develop AraHaul, a multi-modal wireless x-haul testbed for studying long-distance, high-capacity communications. AraHaul, as a part of the ARA PAWR wireless living lab, features state-of-the-art x-haul platforms that operate at diverse frequency bands ranging from 11 GHz and 71–86 GHz to 191.7–194.8 THz and provide communication capacity up to 160 Gbps across distances up to 16 km. We present the design and implementation of AraHaul, including its hardware and software architectures, and illustrate its use to derive insights learned from real-world deployment and operation of long-distance narrow-beam x-haul links. Our illustration consists of an experimental investigation of the behavior of a 10 km-long AraHaul link currently deployed in Central Iowa. We demonstrate the long-distance, high-capacity wireless communications enabled by AraHaul. We also characterize the diversity across multi-modal x-haul links subject to weather, providing insight into mechanisms for robust high-capacity x-haul communications at long distances. AraHaul enables first-of-its-kind studies of multi-modal rural wireless x-haul systems, and its design, implementation, and deployment insights shed light on next-generation rural broadband and advanced wireless systems in general.**

I. Introduction

The rural USA includes 72% of the nation's land and 46 million people, and it serves as a major source of food and energy for the nation. Thus, rural prosperity is essential to US well-being. As a foundation for rural economy and quality of life, rural broadband is a key driver [1]–[3]. Yet 39% of the rural US lacks broadband access, and most agricultural farms are not connected at all [2]–[4]. 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 agricultural farms are far away from their nearest Internet backbone connection points [5], long-distance, high-capacity wireless x-haul networks serve as important "middle-mile" solutions that connect rural towns and agricultural farms with one another and with the Internet fiber backbones [4].

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 and cannot meet the needs of broadband applications alone. Along with the emergence of mmWave communications in wireless access networks, there are recent studies on 71–86 GHz mmWave wireless x-haul systems. Yang et al. in [6] reported their experimental study on 74 GHz mmWave propagation of around 12.2 km distance over the sea between two islands in Sanya, China. The authors analyzed the variation of average received power, cross-polarization ratio, and how those were affected by meteorological conditions by keeping the modulation and symbol rate constant. In [7], Kyro et al. used two different short-distance experimental setups (roof-to-street and street canyon), both covering a distance of 685 m and operating at 81–86 GHz frequency range, to measure channel performance and reception power variations. Brown et al. conducted chip-level design, development, and field testing in [8], where they experimented with four 10 Gbps channels in each direction over a 16.6 km link using the E-band spectrum (71–76 GHz and 81–86 GHz). They observed a 9.53 Gbps data rate with 2 GHz bandwidth and 128 QAM modulation for each channel. These studies mainly focused on the impact of weather conditions on link stability by fixing other parameters. They have not comparatively studied the behavior of x-haul links at different frequency bands, and the question of how to enable robust long-distance, high-capacity x-haul communications remains largely unanswered. In addition, the aforementioned experiments were mostly conducted in a temporary experimental setup or in commercial settings, and there still lack real-world, at-scale x-haul testbeds for enabling long-term experimental studies of multi-modal long-distance, high-capacity rural wireless communications.

As a part of the National Science Foundation (NSF) Platforms for Advanced Wireless Research (PAWR) [9] program, three outdoor large-scale wireless testbeds POWDER [10], COSMOS [11], and AERPAW [12] have been established recently. POWDER focuses on advanced radio access networks (RAN) and massive MIMO (mMIMO) research capabilities, COSMOS features ultra-high-bandwidth and low-latency wireless communication and edge cloud computing platforms, and AERPAW focuses on wireless communications for and with unmanned aerial vehicles (UAVs). However, without focusing on rural broadband and the needs of rural industries such as precision agricultural, the aforementioned testbeds do not address the needs of supporting research in long-distance, high-capacity wireless x-haul networking either.

To fill the aforementioned gaps, we have developed the ARA wireless living lab [4], a first-of-its-kind testbed addressing the unique needs and properties of rural wireless systems. ARA features heterogeneous wireless access platforms as well as multi-modal wireless x-haul systems, operating at diverse frequency bands ranging from 11 GHz and 71–86 GHz to 191.7–194.8 THz, and providing a communication capacity up to 160 Gbps across distances up to 16 km. For convenience, we refer to the ARA x-haul system as *AraHaul*. AraHaul provides a wide range of advanced and flexible configuration options that control parameters such as channel bandwidth, modulation and coding scheme, and transmission power. AraHaul also deploys advanced weather sensors that provide fine-grained weather information such as precipitation type (e.g., rain, snow), drop size distribution, precipitation intensity, particle velocity, visibility, wind speed and direction, temperature, and humidity, facilitating the analysis of weather impact on diverse wireless x-haul channels. Therefore, AraHaul serves as a programmable, at-scale experimental infrastructure for rural wireless x-haul studies.

In this paper, we present the design and implementation of AraHaul, including its hardware and software architectures along with insights learned from real-world deployment and operation of long-distance narrow-beam x-haul links. To illustrate the research studies enabled by AraHaul, we experimentally investigate the behavior of the 10.15 km-long AraHaul link currently deployed in Central Iowa. We demonstrate that the 11 GHz link and 80 GHz link can achieve a capacity up to 925 Mbps and 6.29 Gbps, respectively, at a distance over 10 km. We also characterize the diversity across multi-modal x-haul links subject to weather, for instance, showing the robustness of the 11 GHz with respect to rain and the relatively high rain-sensitivity of the 80 GHz link and higher-order modulation and coding schemes. This observation demonstrates the tradeoff between robustness and capacity, and offers insight into the potential of leveraging diversity for robust high-capacity x-haul communications at long distances. AraHaul enables first-of-its-kind studies of multi-modal rural wireless x-haul systems. The associated design, implementation, and deployment insights shed light on next-generation rural broadband and advanced wireless systems (e.g., 5G and beyond) in general.

The rest of this paper is organized as follows: Section II provides an overview of the ARA wireless living lab and the AraHaul platform. Section III focuses on hardware choice and network architecture of the AraHaul platform. AraHaul software design together with the experimental setup is discussed in Section IV. Measurement results are presented in Section V. Finally, the paper concludes in Section VI with a brief discussion on future work.

II. System Overview

As part of the NSF PAWR program, the ARA wireless living lab consists of two inter-related testbed platforms: AraHaul—a long-distance, multi-hop, multi-radio, high-throughput, low-latency mesh network platform, and AraRAN—a multi-technology radio access network platform for research in 5G and beyond, which consists of programmable commercial-grade as well as software-defined base stations and user equipment. This paper focuses on the design and implementation of AraHaul.

AraHaul employs a set of heterogeneous high-throughput wireless platforms, ranging from microwave and mmWave to free-space optical communications. AraHaul operates at several spectrum bands and provides different capacity-range regions as summarized in TABLE I. The long-distance microwave and mmWave point-to-point communication platforms from the Aviat Networks [13] represent the state-of-the-art in wireless x-haul communication, and it offers programmability, SDN support, and rich APIs for sensing wireless channel behavior (e.g., path loss and interference). The long-distance free-space optical communication (FSOC) platform, called AraOptical [14], has been developed by the ARA project team, and it offers whole-stack programmability as well as high capacity, adaptability, and robustness. As shown in Fig. 1, AraHaul forms a terrestrial mesh spanning 36 miles in diameter, with link distance ranging from 5 to 15 miles, thus enabling research in multimodal, long-distance, high-throughput wireless x-haul communications.

TABLE I: AraHaul wireless link capacity.

Platform	Frequency Range	Max. Bandwidth	Link Capacity
Aviat 11 GHz	10.6–11.5 GHz	100 MHz	1 Gbps
Aviat 80 GHz	71–86 GHz	2 GHz	10 Gbps
AraOptical	191.7–194.8 THz	80 GHz	160 Gbps

Currently, we have completed the design and implementation of one AraHaul link, which is between ISU Agronomy Farm site (monopole deployment) and ISU Wilson Hall site (rooftop deployment), as shown in Fig. 2. The link is marked in red in Fig. 1. The distance between two sites is 6.31 miles. Additional AraHaul links will be deployed in 2024 and 2025, ultimately forming the envisioned mesh topology in Fig. 1.

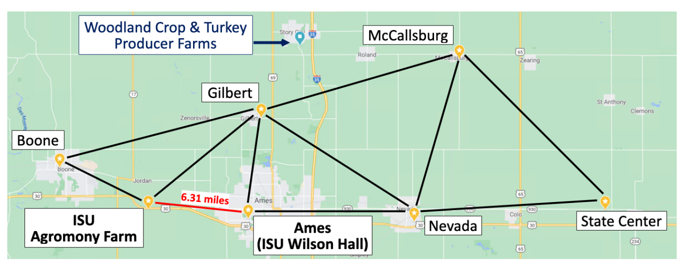


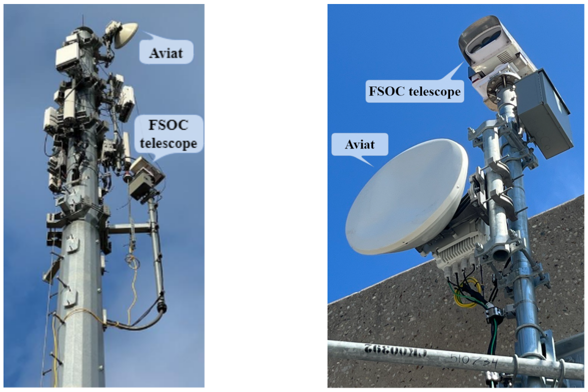
Fig. 1: AraHaul coverage map.

III. Hardware and Network Design

In this section, we discuss the hardware choice and network design of AraHaul, and the lessons learned from field deployment.

A. Hardware Architecture

Fig. 3 illustrates the building blocks of the AraHaul nodes at Agronomy Farm and Wilson Hall.



(a) Agronomy Farm site. (b) Wilson Hall site.

Fig. 2: Aviat dish antennas and FSOC telescopes of AraHaul.

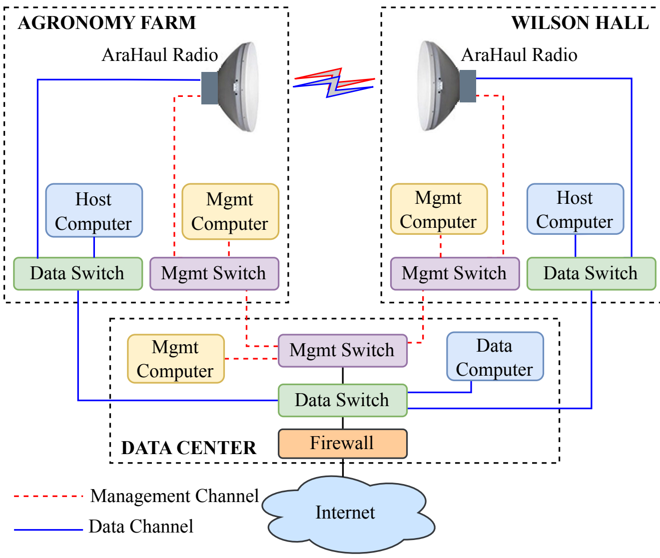


Fig. 3: AraHaul hardware and network architecture.

1) Microwave and mmWave Wireless Links: The microwave and mmWave wireless x-haul links on the ARA testbed is set up using the advanced WTM 4811 radios from Aviat Networks, which represent the state-of-the-art in long-distance point-to-point wireless communication. WTM 4811 is a single box, single antenna, multi-band radio, which operates at both 11 GHz (microwave) and 80 GHz (mmWave) bands. As shown in Table II, it can support up to 1 Gbps and 10 Gbps at the microwave and mmWave bands, respectively. These two carriers can function independently or collaboratively, offering enhanced flexibility in data and management traffic transmission through link adaptation.

2) Free Space Optical Wireless Link: The free space optical wireless x-haul devices (i.e., AraOptical) used on the ARA testbed are designed and assembled in-house by the ARA project team. Operating at the 191.7–194.8 THz band, it is designed to communicate over 10 miles with data rates up to 160 Gbps and is currently in the testing stage.

TABLE II: Aviat wireless link specifications.

Metric	Link	Values
Frequency Band Configuration	mmWave	71–76 GHz (LB) and 81–86 GHz (HB)
	Microwave	11 GHz
Modulation & Coding (Fixed or Adaptive)	mmWave	QPSK to 256 QAM
	Microwave	QPSK to 4096 QAM
Channel Bandwidth	mmWave	250, 500, 750, 1000, 1500, 2000 MHz
	Microwave	3.75, 5, 10, 20, 25, 30, 40, 50, 60 and 80 MHz
Link Capacity	mmWave	up to 10 Gbps
	Microwave	up to 1 Gbps

3) Network Switches and Connectivity: AraHaul radios at Agoronomy Farm and Wilson Hall are connected to both data and management switches, via a 10 Gbps optical fiber-based SFP+ port to the data switch and a 1 Gbps Ethernet port to the management switch. AraHaul radios carry both data and management traffic over the wireless link. The data and management networks are isolated via different VLANs configured on the AraHaul radios. The interface with the management switch is configured in trunk mode to support a dedicated VLAN for the management of the radios. The management switch at each site acts as a gateway for the AraHaul radios on this radio management VLAN, making them reachable over the network for experimental studies.

The connectivity between the data center and the two sites is optical-fiber based. The management channel between the data center and the sites is 10 Gbps SFP+ while the data channel is 100 Gbps QSFP28. The ARA x-haul network runs open shortest path first (OSPF) protocol for routing the traffic of data and management channels between both sites and the data center. The management channel is configured in OSPF Area 1 and the data channel is in OSPF Area 0. Both areas are aggregated in the data center on the data switch to ensure reachability across all networks by leveraging inter-area routing. This design keeps the traffic of data and management channels isolated at each site as can be seen in Fig. 3. The data and management interface over the AraHaul link is also configured with OSPF which completes a Layer-3 ring between the data center, Agronomy Farm, and Wilson Hall sites. Hence, the AraHaul link also acts as a high-capacity backup path for network connectivity in addition to its primary role as an experimental wireless link.

4) Management and Host Computers: Each AraHaul node is equipped with a host computer and a management computer. The host computer connects to the data switch over a 10 Gbps SFP+ interface and is available to users, enabling control of the AraHaul radios for experimental studies on the wireless x-haul links. The management computer is connected to the management switch over a 1 Gbps Ethernet interface and is used for managing and controlling the node-specific operations. Management computers are only available to the administrators of the testbed and run automated scripts to ensure clean state of the nodes before and after the experiments.

5) Weather Sensors: ARA deploys weather stations and disdrometers at both AraHaul sites to facilitate the study on the weather impact on the wireless x-haul channel behavior. Details of the weather sensors are provided in TABLE III. Real-time weather data enables weather-aware wireless research, such as adjustment of the transmission strategy dynamically to the weather condition.

B. Summary of AraHaul Features

To summarize, AraHaul testbed has the following features:

- *Long-distance*: We have implemented a direct and reliable wireless x-haul link between two sites at a long distance

TABLE III: Weather sensors deployed at AraHaul sites.

Weather Sensor Type	Site	Reported Data
Davis Vantage Pro2 [15]	Wilson Hall, Agronomy Farm	Temperature, humidity, wind speed and direction, pressure, rain rate
Lufft WS100 Disdrometer [16]	Agronomy Farm	Precipitation type, drop size distribution, precipitation intensity, particle velocity
Lufft OTT Parsivel^2 Disdrometer [17]	Wilson Hall	Particle size distribution, precipitation type, particle velocity, precipitation intensity, visibility

of 6.31 miles apart. Additional AraHaul links will be deployed to form a mesh topology spannning 36 miles in diameter, as shown earlier in Fig. 1.

- *Multi-radio*: AraHaul testbed is based on multiple wireless technologies, including mmWave links in the E-band (80 GHz), microwave links in the 11 GHz band, and FSOC links in the 194 THz band.
- *Link adaptation*: With multiple radios, AraHaul allows link adaptation to enhance link performance, with the assistance from the weather sensors. For instance, under heavy snow, AraHaul may automatically switch to operate at the more robust mode in the microwave band, ensuring uninterrupted operation and reliable delivery of high-priority data traffic.

C. Lessons Learned

We present below some important lessons learned during the design and field deployment of AraHaul.

a) LOS guarantee: For the wireless x-haul links to function properly over a long distance in real-world environments, it is crucial to ensure line of sight (LOS) between the transmitter and the receiver. In AraHaul, this was accomplished with a thorough investigation of the site conditions, a simulation study of the link parameters using the realistic Aviat Cloud simulator, and a detailed consideration of the possible obstacles between sites such as trees and buildings.

b) Antenna alignment: Fine-tuning antenna alignment is a critical factor in achieving high-throughput wireless x-haul links. For instance, given the extreme narrowness of the beam width of the mmWave link, precise alignment becomes essential to attain a high Signal-to-Noise Ratio (SNR) that is needed to support the higher-order modulation schemes.

c) VLANs and network configuration: VLANs shall be carefully planned for both data and management networks, in order for the network to achieve optimal performance for different types of traffic, thus enhancing the overall efficiency and stability of the system.

d) Site constructions: Selecting appropriate cables for the actual deployment is also important, especially for outdoor installation. Using outdoor-rated cables is of utmost importance to long-term sustainability. Moreover, careful considerations should be given to the cable lengths deployed. For example, when a regular Ethernet cable is used over a distance of 328 feet (100 meters), the signal starts to degrade; hence, power over Ethernet (PoE) extender shall be used.

IV. Software Design and Experimental Setup

A. The AraHaul API

To allow users to conveniently run experiments on AraHaul links, we have developed an AraHaul API to provide a unified interface for the configuration and monitoring of these links. It abstracts over any vendor-specific radio interfaces (e.g., the Aviat CLI for the microwave and mmWave links) and standard radio configuration and monitoring protocols such as NETCONF [18] and SNMP (RFC 3411–3418). It presents users of AraHaul with a standard REST API capable of configuring, checking operational state, and monitoring the wireless x-haul links. TABLE IV lists some of the available endpoints for Aviat radios and their functions.

TABLE IV: AraHaul wireless API endpoints.

Category	API Endpoint	Description
Management	/radio	Enable/disable radio
Management	/carrier	Enable/disable carrier on a radio
Management	/carrier/mute	Mute carrier
Management	/carrier/configure	Configure carrier
Management	/carrier/reset	Reset carrier configuration
Measurement	/radio/capabilities	Fetch radio capabilities
Measurement	/radio/status	Fetch radio operation status
Measurement	/carrier/capabilities	Fetch carrier capabilities
Measurement	/carrier/status	Fetch carrier operation status

Currently, the AraHaul API has implemented the functionality of the Aviat radio CLI, with the integration of additional configuration and monitoring tools, as well as the optical link interface, planned in the future. The API service is packaged as a container, allowing for seamless integration with the broader OpenStack-based ARA software framework that employs a container-based resource provisioning model inspired by the CHI@Edge framework [19]. Furthermore, an AraHaul API client has been developed which can be leveraged by users to interact with multiple API servers deployed at AraHaul nodes.

The AraHaul API is provided as a default layer of abstraction over AraHaul resources. It does not provide complete or fine-grained access to the underlying hardware. A custom API can be implemented alongside (or to supplant) the AraHaul API and made accessible across the ARA platform, highlighting the modularity and extensibility afforded to researchers by the AraHaul software architecture.

B. Experimental Setup

Using the AraHaul API, we have conducted preliminary experimental studies on the capacity of the microwave and mmWave links of AraHaul, and the impacts of the weather conditions on various performance metrics of these links, such as received signal level (RSL) and link throughput. More specifically, we collected measurement data, using a measurement script (described below), for three different x-haul configurations (summarized in TABLE V) for a duration of 6 hours in a round robin manner. The AraHaul link was running under each configuration for 15 minutes, during which RSL values were reported by the Aviat radios, and link

TABLE V: AraHaul link configurations in the experiment.

Config #	Carrier	Bandwidth	Modulation	Tx Power
11 GHz	10.6–11.5 GHz	100 MHz	4096 QAM	26 dBm
80 GHz #1	71–86 GHz	1 GHz	16 QAM	14.5 dBm
80 GHz #2	71–86 GHz	2 GHz	32 QAM	13 dBm

throughput was measured using *iPerf*. Weather data were collected by the weather sensors for the same time duration.

As shown in Fig. 4, a containerized measurement script using the AraHaul API client, which can be launched by the user on either one of the host computers at Agronomy Farm or Wilson Hall site, configures the wireless link and monitors its operational state and performance metrics, then stores the collected data to host disk. This simple experiment script cycles through selected link configurations and records link metrics during each run.

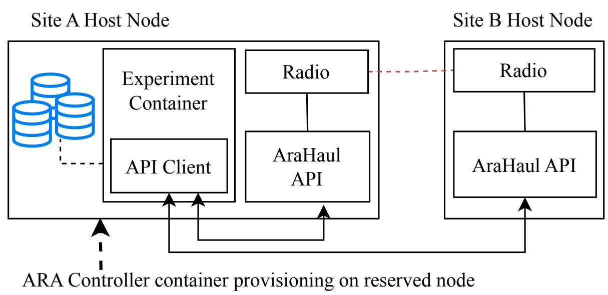


Fig. 4: Software view of the experimental setup.

V. Experimental Results

A. Wireless X-Haul Capacity

At the distance of 6.31 miles (or 10.15 km) between two sites, we observe that the 11 GHz link was able to maintain a steady throughput of 860 Mbps that is close to the theoretical limit of 925 Mbps, regardless of the weather condition. This was accomplished with the maximal allowed bandwidth of 100 MHz, the highest-order modulation of 4096 QAM, and the maximal transmission power of 26 dBm. In contrast, the mmWave link at 80 GHz is less stable at such a long distance of 10+ km and is more susceptible to weather conditions. The highest attainable throughput is around 6.29 Gbps when the bandwidth is set to 2 GHz, the modulation scheme is set to 32 QAM, the transmission power is set to 13 dBm, and when there is no precipitation. This is about 63% of the theoretical limit of 10 Gbps. When a higher-order modulation scheme is used or when there is non-negligible precipitation, the link failed to operate due to the significant signal attenuation and the resulting weak SNR.

B. Impact of Rain Conditions

Fig. 5 plots the measurement results of three different wireless link configurations during a 6-hour period before, during, and after the rain in Ames, Iowa. It is clearly observed that the microwave link at 11 GHz is able to maintain steady RSL and throughput over the entire duration. In contrast, the mmWave link at 80 GHz is more susceptible to weather conditions, and the weather impact is more salient when a higher bandwidth

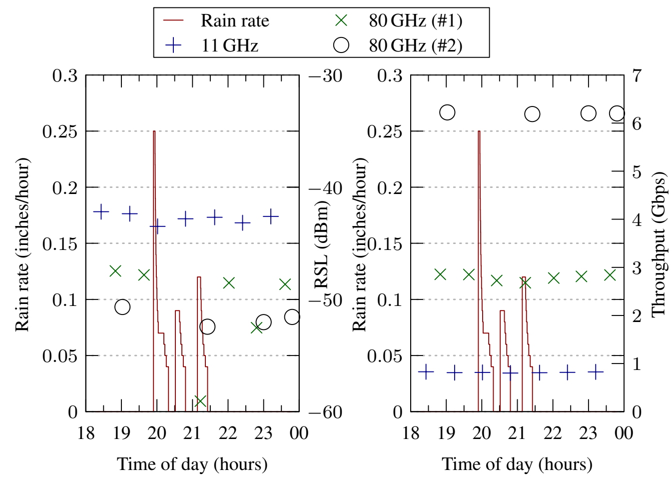


Fig. 5: Behaviors of AraHaul links over a distance of 6.31 miles (or 10.15 km) during a 6-hour time period with varying rain rates. Three groups of results are plotted: 11 GHz ('+' points), 80 GHz Config #1 ('×' points) and Config #2 ('∘' points). Details of the configurations are listed in TABLE V. Rain conditions were reported by the Lufft WS100 disdrometer, RSL data were reported by the Aviat WTM 4811 radio, and link throughput was measured by *iPerf*.

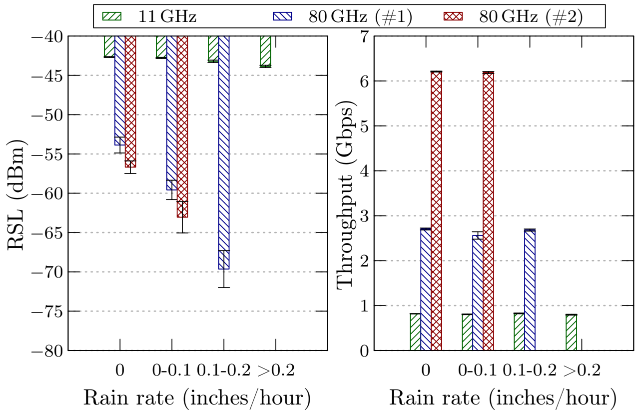
and/or a higher-order modulation scheme are used, as evidenced by 80 GHz Config #2's down time (hence no RSL measurement) and zero throughput around rain.[1]

Figs. 6 and 7 show the measurement result with 95% confidence interval under different rain conditions such as rain rate and raindrop size. Similar phenomena are observed: stable performance of the microwave link regardless of the rain condition; the mmWave link yields a significantly higher throughput under no rain or light rain, however, its performance deteriorates and becomes less predicable when the rain rate or raindrop size increases. The aforementioned results demonstrate the tradeoff between communication capacity and weather-resiliency across wireless links at different frequency bands, as well as the criticality of optimally controlling the operation modes (e.g., channel bandwidth and modulation schemes) of higher-frequency wireless links.

VI. Concluding Remarks

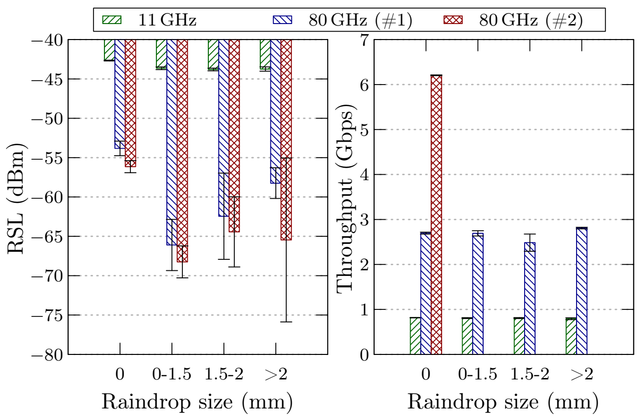
We have presented the design, implementation, and deployment of AraHaul, the first-of-its-kind rural wireless x-haul living lab. Our example experimental study of the microwave and mmWave links of AraHaul has demonstrated its capability of supporting long-distance, high-capacity wireless x-haul communications as well as the associated research investigations. Our study has also demonstrated the rich diversity across wireless x-haul links at different frequency bands. This article serves as an introduction to AraHaul and AraHaul-enabled research, and the associated datasets will be made

[1] Intuitively, one might think that the path loss (PL) of 11 GHz links should be lower than that of 80 GHz links. However, from Fig. 5 and TABLE V, the PL of 11 GHz links is actually higher than that of 80 GHz links. This could be due to a much larger beam width of 11 GHz links, thus leading to a much smaller percentage of signals actually reaching the receiver.



(a) RSL (b) Throughput

Fig. 6: Impact of rain rate on AraHaul links (CI = 95%).



(a) RSL (b) Throughput

Fig. 7: Impact of raindrop size on AraHaul links (CI = 95%).

available to the broad research community for further analysis. AraHaul is currently in beta test phase, and it is expected to be made available for public access in Fall 2023. Besides the example experiment shown in this article, AraHaul will enable a wide range of research investigations. For instance, once the AraOptical part of AraHaul becomes operational, it will further broaden the set of supported experiments within and across long-distance, high-capacity x-haul links at 11 GHz, 71–86 GHz, and 191.7–194.8 THz. AraHaul will also be able to support research investigations such as rigorous modeling of the dynamics, diversity, and weather sensitivity of long-distance, high-capacity wireless x-hauls, experimental study of wireless x-hauls in Open RAN architectures, as well as x-haul control and adaptation mechanisms to support application-specific Quality-of-Service (QoS) and Quality-of-Experience (QoE) requirements (e.g., those in real-time agricultural automation and XR-based rural education). Together, these research studies are expected to generate foundational insights and systems prototypes for next-generation x-haul solutions in rural broadband and advanced wireless in general.

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