

Design and Implementation of ARA Wireless Living Lab for Rural Broadband and Applications

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Abstract

To address the rural broadband challenge and to leverage the unique opportunities that rural regions provide for piloting advanced wireless applications, we design and implement the ARA wireless living lab for research and innovation in rural wireless systems and their applications in precision agriculture, community services, and so on. ARA focuses on the unique community, application, and economic context of rural regions, and it features the first-of-its-kind, real-world deployment of long-distance, high-capacity wireless x-haul and access platforms across a rural area of diameter over 30 km. With both software-defined radios and programmable COTS systems and through effective orchestration of these wireless resources with fiber as well as compute resources embedded end-to-end across user equipment, base stations, edge, and cloud, ARA offers programmability, performance, robustness, and heterogeneity at the same time, thus enabling rural-focused co-evolution of wireless and applications while helping advance the frontiers of wireless systems in domains such as O-RAN, NextG, and agriculture applications. Here we present the design principles and implementation strategies of ARA, characterize its performance and heterogeneity, and highlight example wireless and application experiments uniquely enabled by ARA.

1 Introduction

Much like water and electricity, broadband Internet access has become an essential utility. Its significance extends to our professional, educational, and personal lives, as well as to various industries (e.g., precision agriculture) and community services (e.g., public safety). Nonetheless, 39% of the rural U.S. and 75% of school-age children in rural regions worldwide lack broadband access, most agriculture farms are not connected at all, the current terrestrial broadband technologies are largely not optimized for rural regions, and satellite communications incur larger latency (e.g., over 100 ms even for LEO systems) and offer relatively more limited capacity than the latest terrestrial communication systems such as

5G [21, 26]. In addition, broadband evolves at a fast pace, and new generations of technologies and services get rolled out every 5–10 years in and around urban regions. Therefore, besides addressing today’s rural broadband challenge through mechanisms such as government subsidy, we need to make sure rural regions do not perpetually lag behind urban regions in broadband access, and we need to enable rural-focused wireless technology research and innovation.

At the same time, rural regions provide rich, diverse use cases of advanced wireless systems, ranging from crop nitrate sensing to 360° video streaming for rural education, XR-based teleoperation of unmanned ground vehicles (UGVs) and unmanned aerial vehicles (UAVs) for precision farming, collaborative UGVs and UAVs in agriculture automation, and so on. In fact, rural regions provide unique real-world opportunities for piloting applications such as UGV and UAV teleoperation to mature emerging wireless technologies and applications in open rural settings before their trials in dense urban environments, thus helping advance the frontiers of wireless systems in general.

To address the rural broadband challenge and to leverage the rural wireless opportunities, we develop the ARA wireless living lab [26] for research and innovation (R&I) in rural wireless systems and their applications in precision agriculture, community services, and so on. The design and implementation of ARA feature the following distinguishing *principles*.

Rural context. To support rural-focused R&I, ARA captures the unique community, application, and economic context of rural wireless systems through its deployment across a rural area of diameter over 30 km and including the Iowa State University campus, City of Ames, and surrounding research and producer farms as well as rural communities in Iowa. In addition, ARA features the first-of-its-kind, real-world deployment of long-distance, high-capacity wireless x-haul and access platforms. With wireless x-haul platforms operating at the 11 GHz, 71–86 GHz, and 194 THz bands and offering communication capacities up to 160 Gbps at distances up to 15+ km, the ARA x-haul exemplifies low-cost, high-capacity middle-mile solutions connecting remote rural communities and agriculture farms to the nearest wired Inter-

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net backbone. With 5G-and-beyond Multiple-Input Multiple-Output (MIMO) systems operating at the 460–776 MHz, 3.4–3.6 GHz, and 27.5–28.35 GHz bands and with 14, 192, and 384 antenna elements per sector, respectively, the ARA radio access network (RAN) exemplifies massive MIMO wireless access platforms that offer high capacity and large cell radius through beamforming, thus reducing the required spatial density of RAN base stations and cost of rural wireless.

Wireless and application co-evolution. With a sharp focus on rural wireless applications and for engaging application communities in the R&I process, ARA supports *programmability and measurability* for both wireless and application R&I. More specifically, ARA embeds open-access compute resources end-to-end across UEs, BSes, edge, and cloud, thus enabling programmability and measurability at the network, transport, and applications layers. For link and physical layer programmability and measurability, ARA uses software-defined-radios (SDRs) for full programmability and measurability at the UEs and BSes, and it employs commercial-off-the-shelf (COTS) RAN and x-haul platforms that have rich APIs for link and physical layer configuration and measurement, including the first-of-its-kind open API for a television-white-space (TVWS) massive MIMO platform. To ensure high *performance and robustness* that are required by application communities but challenging to achieve for early-stage wireless R&I, ARA employs high-performance, mature COTS 5G-and-beyond RAN platforms as well as high-capacity, long-distance wireless x-haul platforms, it deploys high-performance compute resources end-to-end from UEs to the cloud, including the deployment of GPUs at the edge and cloud for applications such as real-time image processing. The design of ARA facilitates the use of spatial, temporal, and spectral diversity to improve the robustness of x-haul and RAN communications, and the use of weather sensors for predictive network adaptation.

Efficient, Trustworthy & Reproducible Experimentation. For effective resource management and experiment orchestration, we architect ARA such that its wireless x-haul and access platforms are managed by their associated compute resources (e.g., host computers). This way, ARA can leverage OpenStack [16] software platform to manage its compute resources and then extend OpenStack to manage ARA’s wireless x-haul and access resources, for instance, orchestrating resource allocation to avoid wireless interference between concurrent experiments and safe-guarding ARA from misbehaving wireless experiments that may violate wireless spectrum use specification. The use of widely-accepted software platforms such as OpenStack and Docker [4] in ARA helps minimize the learning curves of ARA users, it facilitates the potential translation of ARA-enabled research results into industry practice (e.g., in the OpenStack ecosystem), and it enables ready integration of ARA with other national cyberinfrastructures such as the programmable network backbone

FABRIC [15] and the research cloud Chameleon [3]. Further, ARA provides a programmable profile interface with support for Jupyter Notebook [12], allowing users to specify, share, and reproduce experiments in a rigorous and effective manner, thereby enabling reproducibility and community collaboration in ARA-enabled research.

With first-of-its-kind deployment of advanced wireless and computing platforms in real-world agriculture and rural settings and through effective resource management and experiment orchestration, ARA enables unique R&I experiments in a wide range of topics such as those in O-RAN, open-source NextG, TVWS massive MIMO, spectrum innovation, integrated rural wireless access and x-haul, 360° video streaming, real-time edge data analytics, and agriculture automation. In what follows, we elaborate on the ARA design and implementation in Sections 2 and 3, respectively. We evaluate the performance and heterogeneity of ARA, and we present exemplars of ARA-enabled wireless and application experiments in Section 4. We discuss related work in Section 5, and make concluding remarks in Section 6.

2 Design of ARA

2.1 ARA Deployment for Capturing Real-World Rural Context

Rural communities tend to be sparsely distributed, with inter-community distances being tens of kilometers or more. These communities, together with surrounding agriculture farms, are usually far away from the wired Internet backbone. The generally sparse user spatial distribution makes it not economically viable to pervasively deploy in rural regions urban-focused broadband technologies such as fiber and small cells; we need affordable *middle-mile* solutions to connect rural communities and agriculture farms with one another and the Internet, and affordable *last-mile* solutions to connect end-user devices such as automated ground and aerial vehicles in precision agriculture [26]. This unique community and economic context motivates the use of two broad categories of terrestrial wireless solutions in rural regions: high-capacity, long-distance wireless x-haul networks as middle-mile solutions and high-capacity wireless access networks as last-mile solutions.

Accordingly, we design ARA so that its deployment covers a rural area of diameter over 30 km and includes Iowa State University campus, City of Ames, and surrounding research and producer farms as well as rural communities in Iowa, as shown in Figure 1. ARA consists of AraHaul and AraRAN. AraHaul is a high-capacity wireless x-haul mesh network spanning City of Ames, Ag Research Farm, Boone, and Gilbert. AraRAN is a high-capacity Radio Access Network (RAN) with Base Stations (BSes) deployed at every AraHaul site as well as Curtiss Farm and Research Park. Gilbert, Boone and ISICS Tower sites will be fully deployed by the end of summer 2024 while Nevada, McCallsburg and State Center sites will be deployed in Phase-3 of ARA. The de-

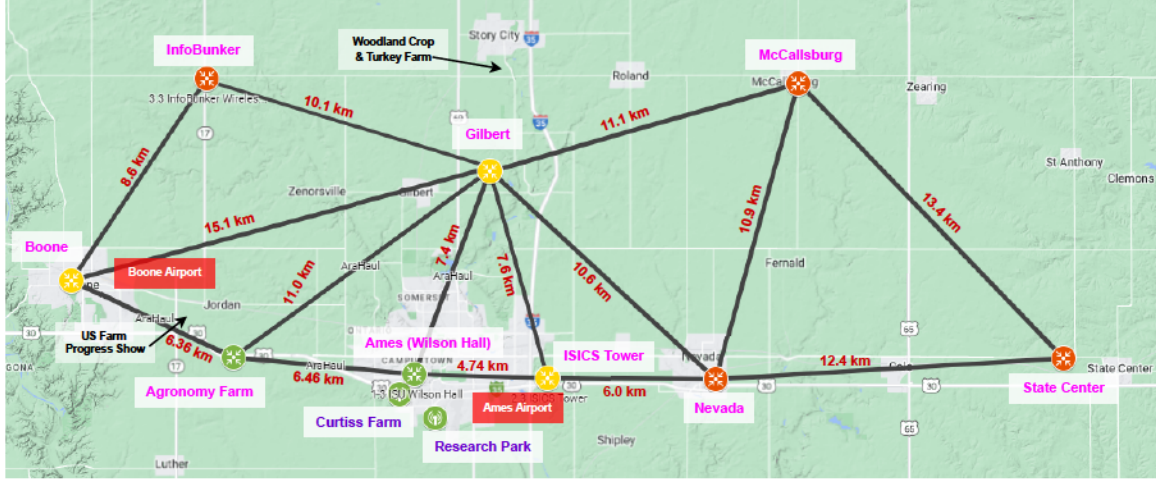


Figure 1: ARA Deployment

ployment of ARA around the Iowa State University campus and the Research Park that host corporate research centers of leading AgTech and avionics companies such as John Deere, Vermeer, and Collins Aerospace helps engage industry in ARA-enabled application innovation, which in turn drives innovation in advanced wireless.

To capture the application context of rural wireless, ARA deploys User Equipment (UEs) across agriculture farms and rural communities around the AraRAN sites. The UE deployment features both crop and livestock farms, farm facilities (e.g., grain mills, grain bins, and biorefineries), as well as agriculture vehicles, robots, UAVs, and phenotyping cameras and sensors. In rural communities, the UEs are deployed at city water towers, municipal airports, buses, and public safety vehicles such as fire and police vehicles. The UE deployment captures diverse rural wireless use cases in agriculture and communities, and it enables integrative wireless and application experiments in real-world rural settings, thus facilitating wireless and application co-evolution.

2.2 ARA Architecture and Platforms for Wireless and Application Co-Evolution

2.2.1 ARA System Architecture

To enable high-fidelity wireless and applications experiments, ARA is architected to reflect real-world architectures of rural wireless systems, as shown in Figure 2.

More specifically, the ARA infrastructure consists of the *device stratum*, *edge stratum*, and *cloud stratum*, reflecting the device-edge-cloud continuum in today's wireless and application infrastructures. The *device stratum* includes the ARA UE stations together with application-specific equipment and their associated sensors and actuators (e.g., agriculture vehicles with high-resolution imaging sensors and weed-sprayer-nozzles). The *edge stratum* includes the ARA BS sites and

the networks (e.g., AraHaul) connecting these BS sites to one another. The edge stratum provides wireless connectivity to the ARA UE stations, it provisions edge computing resources for processing time-sensitive data from the device stratum, and it connects the device stratum to the cloud stratum for enabling cloud resource access by rural applications such as agriculture automation. The *cloud stratum* includes the ARA lab core where the AraController as well as wireless- and application-oriented cloud compute, storage, and network resources are provisioned. As we will discuss in more detail in Section 2.3, the AraController manages ARA resources and orchestrates experiments in ARA. Through the National Science Foundation (NSF) FABRIC network [15] and Internet, ARA is connected to other experimental infrastructures such as the Chameleon cloud [3].

To enable end-to-end orchestration of the resources from the device, edge, and cloud strata for experiments, the resources at the ARA UE stations, BS sites, and lab core are organized into the experiment plane and management plane, supporting wireless and application experimentation and ARA management respectively. In the *experiment plane*, both the UE stations and BS sites have the rural-focused AraRAN wireless platforms, most BS sites have rural-focused AraHaul wireless platforms, a subset of the BS sites have edge compute resources, and the lab core has cloud compute and network resources. All the BS sites and the lab core are connected through dedicated fiber networks and/or AraHaul wireless platforms. All the BS sites and UE stations have RF sensors, and a subset of the BS sites also have weather sensors; these *RF and weather sensors* enable spectrum innovation research and the characterization of weather impact on rural wireless communications. The UE stations, BS sites, and lab core have *smart Power Distribution Units (PDUs)* to enable the power consumption measurement and on/off control of the individual equipment, thus enabling research in energy-efficient wireless systems and applications. In the *management plane*, the

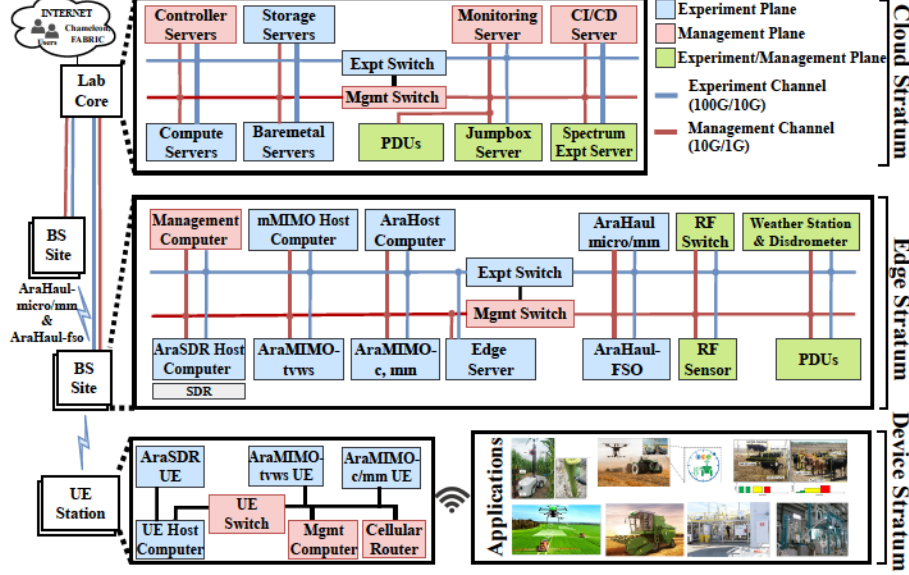


Figure 2: ARA System Architecture

lab core has dedicated servers for controlling ARA resource management and experiment orchestration, monitoring ARA health status and spectrum use integrity, and managing the continuous evolution of the ARA software systems and associated Continuous Integration and Continuous Deployment (CI/CD) processes. The BS sites and UE stations have dedicated management computers that interact with the lab core in resource management and experiment orchestration. The BS sites connect to the lab core through a dedicated management network of fibers and wireless backhauls, and the UE stations connect to the lab core through management paths provided by commercial cellular networks. The data traffic in the experiment plane and management plane is isolated from each other since each plane has its own dedicated network or VLAN. The UE stations, BS sites, and lab core are architected so that new devices can be easily integrated into the experiment plane and management plane, thus facilitating Bring Your Own Device (BYOD) experiments.

2.2.2 ARA Experiment Platforms

To support *diverse rural use cases*, ARA features heterogeneous wireless access and x-haul platforms, as shown in Table 1. Despite the generally sparse spatial distribution of users, the UE spatial density in rural cities and communities as well as during the busy periods of agriculture farms (e.g., the weeks of harvesting season in early fall) can be close to that in suburban or even urban regions. Therefore, AraRAN adopts massive MIMO wireless access platforms spanning the low-band, mid-band, and high-band, and they exemplify wireless systems that offer high capacity and large cell radius through beamforming, thus reducing the required spatial density of RAN base stations and the cost of rural

Table 1: Heterogeneous, High-Capacity Wireless Access and X-Haul Platforms in ARA

	Platform	Frequency	Bandwidth	Capacity	Range
AraRAN	AraMIMO-TVWS	460–776 MHz	upto 40 MHz	100+ Mbps	8.5+ km
	AraMIMO-C	3.45–3.55 GHz	100 MHz	650+ Mbps	8.5+ km
	AraMIMO-mm	27.5–27.9 GHz	4 × 100 MHz	1.3+ Gbps	500+ m
	AraSDR	3.4–3.6 GHz	200 MHz	100+ Mbps	1.2+ km
AraHaul	AraHaul-micro	10.6–11.5 GHz	100 MHz	1 Gbps	20+ km
	AraHaul-mm	71–86 GHz	2 GHz	10 Gbps	15+ km
	AraOptical	191.7–194.8 THz	80 GHz	160 Gbps	10+ km

wireless. Similarly, AraHaul leverages diverse long-distance, high-capacity x-haul platforms; it employs the 11 GHz and 71–86 GHz x-haul COTS platforms from Aviat Networks, denoted by AraHaul-micro and AraHaul-mm respectively, and it features the first-of-its-kind long-distance terrestrial free-space optical communications platform AraHaul-fso which we develop for ARA (see Section 3.3). These AraHaul platforms exemplify low-cost, high-capacity middle-mile solutions for rural regions.

Regarding AraRAN, the *low-band* AraMIMO-tvws platform utilizes the COTS Skylark Faros massive MIMO system at the TVWS band; with 14 antenna elements per sector, it provides a cell coverage up to 10+ km and per-user-group communication capacity up to 100+ Mbps at the same time, thus suitable for connecting UEs in the country side and far away from the base stations. The *mid-band* AraMIMO-c platform utilizes the COTS Ericsson AIR 6419 massive MIMO system operating at the 3.4–3.6 GHz band; with 192 antenna elements per sector, it provides a cell coverage up to 8.5+ km and per-user-group communication capacity up to 650+ Mbps, thus suitable for connecting general UEs in the city/community center and agriculture farms. The *high-band* AraMIMO-mm platform utilizes the COTS Ericsson AIR

5322 mmWave system operating at the 27.5–28.35 GHz band; with 384 antenna elements per sector, it provides a cell coverage up to 500+ meters and per-user-group communication capacity up to 1.3+ Gbps, thus suitable for dense city centers and during the busy periods of agriculture farm operations. The mid-band portion of AraRAN also uses USRP SDRs N320 and B210 to support open-source NextG and O-RAN experiments.

For rural-focused wireless and application R&I, AraRAN and AraHaul, together with the ARA platforms for compute, weather and RF sensing, as well as power metering and control, support *whole-stack programmability and measurability*. As shown in Figure 2, open-access compute resources are embedded end-to-end across UE stations, BS sites, and lab core. Together with open-source software systems such as the Ubuntu Linux operating system and softwareized telecom and application platforms (e.g., Open5GS, DPDK, QUICHE, and GStreamer), these compute resources enable programmability and measurability at the *network, transport, and application layers* to support experiments at these layers across all ARA wireless and compute platforms. For programmability and measurability at the *link and physical layers*, the USRP SDRs N320 and B210, together with open-source 5G software platforms such as OpenAirInterface, srsRAN, and O-RAN Software Community systems, enable full programmability at the AraRAN BS Sites and UE stations. Through effective *software wrappers* (as we will elaborate in Section 3.4), ARA also provides rich APIs for configuring and measuring the link and physical layers of its COTS wireless access and x-haul platforms, including the first-of-its-kind open API for the TVWS massive MIMO platform AraMIMO-tvws. ARA also uses similar software wrapper approaches to enable the configuration of and measurement with weather and RF sensors as well as smart PDUs. Therefore, ARA enables comprehensive measurement of wireless channel and link behavior (e.g., channel path loss, massive MIMO channel state matrix, and link bit error rate), weather condition (e.g., rain rate and rain-drop size), and equipment power consumption, and it enables configuration of important link and physical layer behavior of wireless platforms (e.g., massive MIMO user grouping and beamforming, operating frequency, transmission power, as well as modulation and coding schemes).

The design of ARA also pays special attention to the *performance and robustness* required by wireless and applications R&I. For instance, application R&I tend to require performance and robustness that are challenging to achieve for early-stage wireless R&I and commonly used open-source 5G platforms (e.g., OpenAirInterface). ARA addresses the challenge by employing high-performance, mature COTS 5G-and-beyond RAN platforms as well as high-capacity, long-distance wireless x-haul platforms while enabling whole-stack programmability as mentioned earlier. Together with the diverse operation frequencies of AraRAN and AraHaul platforms, the mesh network topology and the specific designs

of the ARA BS sites and UE stations (see Sections 3.1 and 3.2) also facilitate the use of spatial, temporal, and spectral diversity as well as weather-sensor-enabled predictive network adaptation to improve the robustness of x-haul and RAN communications in inclement weathers.

The ARA compute and storage resources have also been carefully designed to support the needs of wireless and application R&I. For instance, the compute and baremetal servers at the Cloud Stratum have high-performance specs (e.g., 3 GHz and 48 Core Intel Xeon 6326 CPU, 384 GB RAM) for functions such as those of 5G core networks and real-time data processing. The storage servers are equipped with 28 TB storage each and in RAID 5 configuration to ensure fault tolerance. At the Edge Stratum, each SDR host computer supports three SDRs and has high-performance specs (3.1 GHz, 16 Core Intel Xeon 6346 CPU, 64 GB RAM) for open-source 5G signal processing and high-layer network stacks. The edge stratum also hosts edge servers with NVIDIA RTX 5000 GPUs for real-time processing of application data such as the multi-spectral, high-resolution imaging data used in agriculture automation [34].

At the Device Stratum, the UE host computers (with 2.7 GHz, 8 Core Intel Xeon D-1736NT CPE, 32 GB RAM) support experiments with UE SDRs as well as AraMIMO-tvws, AraMIMO-c, and AraMIMO-mm UEs.

2.3 Efficient, Trustworthy and Reproducible Experimentation

To manage the heterogeneous ARA resources and orchestrate diverse user experiments with maximum automation, we develop the ARA software framework AraSoft. AraSoft has the following key features:

- **Efficiency.** AraSoft leverages OpenStack [16] to achieve efficient resource management and provisioning. Moreover, we employ a set of best practices (e.g., CI/CD [9]) to ensure that ARA is efficient and sustainable in terms of long-term maintenance and evolution.
- **Trustworthiness.** AraSoft includes fine-grained health monitoring, fault tolerance (e.g., hardware RAID [23] and software replication), and security mechanisms to ensure the reliability and security of ARA experiments.
- **Reproducibility.** In addition to an intuitive graphical user interface, AraSoft provides a programmable profile interface with support for Jupyter Notebook [12], allowing users to specify, share, and reproduce experiments in a rigorous and effective manner. Moreover, it includes a rich set of APIs to enable the customization of heterogeneous wireless platforms for reproducible experiments.

We elaborate on a few key design tradeoffs of AraSoft below. First, unlike many other testbeds [8, 18, 24, 31, 45] which are based on in-house software, we develop AraSoft based

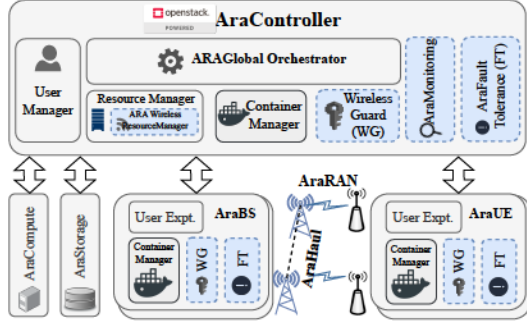


Figure 3: ARA-Soft Overview (Blue dash-lined boxes denote the components newly introduced by ARA-Soft atop OpenStack).

on the foundation of OpenStack, a proven open-source cloud platform in production. This design decision brings multiple benefits, including leveraging the collective wisdom and experiences from the broad open-source community, specifically Chameleon Cloud [28, 29], and contributing back to the community to co-shape the future. In addition, the rich set of cloud services in OpenStack, including user and resource management, networking, and orchestration, make it a best-fit baseline for AraSoft.

With the solid foundation, we further introduce a set of unique functionalities to support the ARA vision. As shown in Figure 3, AraSoft consists of 1) ARA-Controller for overall user management and experiment control, 2) ARA-BS and ARA-UE for BS and UE management, and 3) ARA-Compute and ARA-Storage for compute and storage management, respectively. The blue dash-lined boxes highlight the new components that AraSoft introduces to the OpenStack ecosystem.

More specifically, ARA-Controller serves as the operating system for ARA. It includes a *User Manager* for user authentication and access control (e.g., federated login via Globus [2]), a *Resource Manager* for resource pool management, and a *Container Manager* for executing containerized experiments. It takes less than 15 seconds for the ARA Resource Manager to create a resource lease on a user request; the time for launching experiment containers varies depending on the size of the container image, with $\sim 80\%$ of the time spent for downloading the image and the remaining $\sim 20\%$ for creating and starting the experiment container. Moreover, there is a *Global Orchestrator* to coordinate all the activities with dedicated security and reliability support (e.g., LibreNMS [5] and Prometheus [17] based ARA-Monitoring, redundancy-based ARA-Fault Tolerance).

One of the most important capabilities of ARA-Soft is *Wireless Guard* (WG) [39]. In ARA living lab, concurrent users may share resources that use wireless spectrum of various bands. To provide the necessary isolation and ensure the compliance of spectrum usage, the WG modules in ARA-BS and ARA-UE continuously monitor the spectrum usage of experiments and coordinate with the WG module in ARA-

Controller. In case of any violation in usage policy or experiment specification, the WG terminates the offending experiment immediately. Besides the dynamic checking, WG can enforce the security further through strict access controls in ARA experiment APIs.

2.4 ARA-Enabled Research

With first-of-its-kind deployment of advanced wireless and computing platforms in real-world agriculture and rural settings and through effective resource management and experiment orchestration, ARA enables unique research experiments ranging from the modeling to the architectures, technologies, services, and applications of rural wireless systems, as shown in Table 2. They cover a wide range of topics such as those in O-RAN, open-source NextG, TVWS massive MIMO, spectrum innovation, integrated rural wireless access and x-haul, 360° video streaming, real-time edge data analytics, and agriculture automation. In Section 4, we will characterize the capacity, coverage, and heterogeneity of ARA, and delve into example wireless and application experiments to showcase the capabilities of ARA.

Table 2: ARA-Enabled Research

Areas	Exemplars
Modeling	- Real-world rural wireless channel characterization - Real-world characterization of physical dynamics and mobility of agriculture UAVs and UGVs
Network Architecture	- O-RAN architecture for real-time cyber-physical systems of agriculture vehicles and robots - Multi-modal, long-distance, and high-throughput wireless x-haul networking - Integrated rural wireless access and x-haul networking - Integrated wireless networking and edge computing
Technology & Service	- Ultra-reliable, low-latency communications (URLLC) - Massive MIMO, beam-forming, and beam tracking - Dynamic spectrum sharing - Open-source NextG for rural green networking
Application	360° video streaming for agriculture education - Real-time video streaming and analytics for agriculture automation and livestock health monitoring - XR-based teleoperation of agriculture UAVs

3 Implementation of ARA

3.1 Base Station (BS) Site

The BS site has AraRAN BS and AraHaul nodes as shown in Figure 2. The physical installation of four representative BS sites is shown in Figure 4. The heights and locations



Figure 4: Physical BS installation

of the BSeS have been carefully chosen through coverage simulations and field testing.

AraRAN BS. Each AraRAN BS hosts three AraSDR (NI N320 [14]), three AraMIMO-c (Ericsson AIR 6419 [11]), three AraMIMO-mm (Ericsson AIR 5322) radios, with residence hall hosting additional three AraMIMO-tvws (Skylark Faros V2 [1]) Radio Units (RUs), enabling a diverse range of operations and experimentation with respect to coverage, capacity, and programmability. Figure 5 shows our design of the AraSDR BS architecture [19]. Each SDR is connected

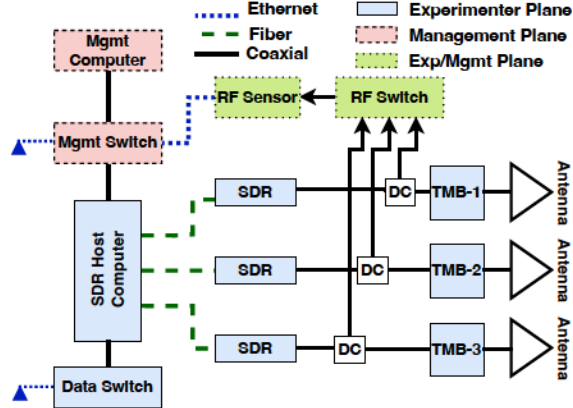


Figure 5: Architecture of Field-Deployed SDR BS

to a band 78 Time Division Duplex (TDD) Tower Mounted Booster (TMB) comprising of a Power Amplifier in the transmit chain and Low Noise Amplifier (LNA) in the receive chain. Each TMB is connected to a commscope SS-65M-R2 antenna. The three commscope antennas covers a 360° cell. The Directional Coupler (DC) and RF Sensor are for wireless guard as discussed in Section 2.3. The SDRs, along with the TDD frontends, support open-source 5G and O-RAN experiments using software platforms such as OpenAirInterface5G [7].

AraHaul Node. AraHaul [48] enables long-distance, high-capacity, and affordable x-haul connectivity to rural areas. AraHaul nodes are installed at Ag Research Farm 1, Reseidence Hall, school district tower, and public safety towers 1 and 2, thus forming a wireless x-haul mesh network in real-world rural environment. The exact locations and heights of the AraHaul radios are carefully planned to ensure line of sight (LOS) path. In our study, we conducted thorough LOS testing over distances up to 10.5 km using various optical sighting tools, including rifle scope, spotting scope, astronomical telescope, and visible laser source. The AraHaul platforms are programmable through wrapper APIs as discussed in Section 3.4.

3.2 User Equipment (UE) Station

The UE stratum consists of AraRAN UE and the associated sensing, control, and/or actuation devices.

Each UE has three radios, i.e., USRP B210 SDR, Skylark Wireless CPE, and Quectel COTS 5G UE. Each UE has a SuperMicro mini-server host computer that runs the 5G protocol stack for NI B210 SDR, software drivers for Quectel COTS UE, and Skylark Wireless application for the Skylark CPE. The host computer is available to experimenters as a compute resource for programmable experiments. AraRAN UE has a Juniper EX2300 switch that ensures connectivity between all elements on the AraRAN UE. The management computer runs management and control applications such as spectrum monitoring and remote power management. The USRP B205 SDR is deployed at each UE location for spectrum sensing and spectrum policy enforcement through wireless guard. One Cradlepoint IBR600C cellular router is also installed at each UE station with a commercial LTE SIM card, serving as a backup management channel. Figure 6 shows a field-deployed UE with Skylark CPE and antenna, SDR antenna, Cradlepoint router antenna, and COTS UE box deployed on a pole. The figure also shows a mobile UE in a phenotyping robot (phenobot) and a fixed UE deployed in a crop farm. A UE box with computers, switch, and SDRs inside is also shown.

3.3 AraHaul-fso Communications System

AraHaul-fso is a first-of-its-kind long-distance, high-capacity terrestrial free-space-optical-communication (FSOC) platform, capable of achieving up to 160 Gbps data rate over 10 km aerial distance in rural environments. Figure 7 shows the architecture of the AraHaul-fso signal branch. Each node employs 16 wavelength-division-multiplexing (WDM) channels, each using an SFP+ transceiver operating at 10 Gbps. These transceivers connect to an optical module with an erbium-doped-fiber-amplifier (EDFA) for signal amplification. The amplified signal beam is transmitted over-the-air using an optical collimator (CL) with a 35 μ rad divergence angle, significantly reducing geometric losses. The Circulator separates the received signal from the transmitted signal and forwards the received signal to the WDM device for demultiplexing. To enable LOS FSOC at long distance, the AraHaul-fso platform has a carefully designed system for self-alignment using mechanisms such as the beacon signal which has exactly the same LOS path as the data signal but has much wider beamwidth and thus easy to align.

AraHaul-fso offers first-of-its-kind terrestrial FSOC measurability and programmability through wrapper APIs. These

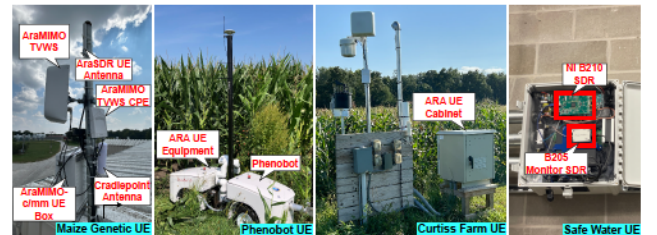


Figure 6: ARA Field deployed UEs

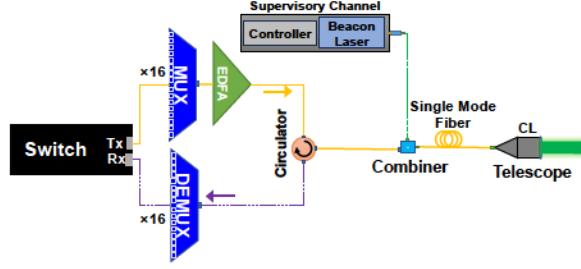


Figure 7: Architecture of AraHaul-fso Signal Branch

APIs enable the measurement of parameters such as reception power, throughput, and communication latency from switch interfaces. The APIs also enable controls such as transmission power and bitrate adaptation, beam steering, and routing.

3.4 Programmability for COTS Platforms

To enable programmability of COTS platforms while leveraging their performance and robustness in wireless and application experiments, we develop wrapper APIs that expose system configuration and control according to experiment requirements while ensuring the system integrity from potential experiment misbehavior. More specifically, for the AraMIMO-tvws platform [27] with hardware and software access control, we define modding APIs capable of executing custom user scheduling and grouping algorithms, along with wrapper APIs for the configuration and control of the TVWS massive MIMO BSes and UEs. For the AraMIMO-c, AraMIMO-mm, and AraHaul platforms, we define wrapper APIs around the device-level functions to enable programmability and measurability while ensuring safety through strict access control. Besides AraRAN and AraHaul, ARA includes resources (e.g., weather sensors and PDUs) which do not need explicit resource reservation for their use in experiments, that is, the devices can be polled for weather and power-related measurements concurrently by multiple users at any given time. A dedicated server along with custom APIs are developed for users to collect the most recent as well as historical weather and power consumption information. The wrapper APIs for each platform are containerized and made available to ARA users for research experiments.

4 ARA Capacity, Coverage and Experiments

In what follows, we demonstrate the performance, heterogeneity, programmability, and measurability of ARA by characterizing its capacity and coverage and by showcasing example wireless and application experiments.

4.1 ARA Capacity and Coverage

4.1.1 AraRAN Capacity and Coverage

AraRAN Capacity Characterization. To characterize the capacity of the heterogeneous AraRAN platforms, we mea-

sure the link capacity in the south sector of the Wilson Hall BS. The data collection involves simultaneous measurements at several distances from the BS. AraMIMO-mm and AraMIMO-c are transmitting at 128 W while AraMIMO-tvws is transmitting at 10 W, which is the maximum power supported for each platform. AraSDR is transmitting at 10 mW which is the optimal transmit power for maintaining stable open-source 5G connections between SDR-based UEs and BSes in the ARA outdoor environments using the develop branch of OpenAirInterface5G. The measurements are taken starting at 170 m up to 8.6 km from the BS. The first six points are roughly 100 m apart while the remaining points are approximately 350 m apart. Several crop and livestock research farms are located along this route, making it an ideal route for rural- and ag-focused study.

Figure 8 shows that AraMIMO-mm provides the maximum downlink (DL) capacity of 1.3+ Gbps / 400 MHz with coverage up to 500 m (Point A) from the BS. AraMIMO-c and AraMIMO-tvws achieve the maximum DL capacity of 650+ Mbps 100 MHz and 120 Mbps / 24 MHz respectively, with decent coverage up to 8.6+ km. The use of AraSDR is primarily for its full programmability and not for capacity, but AraSDR still enables a capacity of 25+ Mbps / 40 MHz up to 1.2+ km distance. About 1.6 km from the BS (Point B), the terrain has a severe dip in elevation which prevents UEs from connecting to the BS due to severe signal blockage. There are some locations between Points C and D (4.5–6 km) from BS where AraMIMO-c shows no coverage due to blockage by trees and farm buildings but AraMIMO-tvws can still connect to the BS. As the elevation goes up around 6.5 km (Point D), the AraMIMO-c UE is able to reconnect to the BS. We see that there is almost uniform coverage up to 3 km distance and then there emerges that transition region where the capacity varies due to terrain conditions. For characterizing the heterogeneity of ARA, we also evaluate the AraMIMO-c and AraMIMO-mm BS with the same transmission power as AraMIMO-tvws (i.e., 10 W). We see that the coverage is reduced to 2 km and 300 m for AraMIMO-c and AraMIMO-mm respectively.

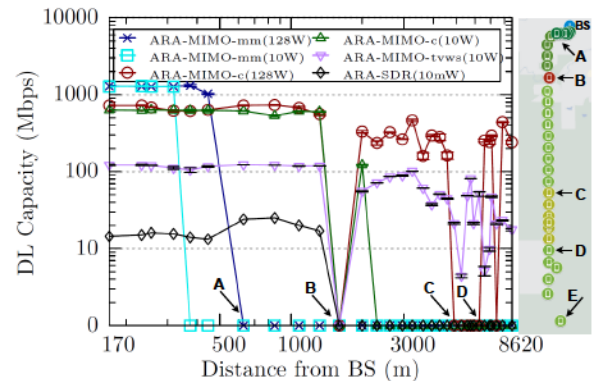


Figure 8: Coverage and capacity comparison of AraMIMO-mm, AraMIMO-c, AraMIMO-tvws and AraSDR platforms.

AraRAN Coverage Characterization. For understanding opportunities for wireless and application co-evolution studies, we also characterize the large coverage of the COTS platforms AraMIMO-c and AraMIMO-tvws. For AraMIMO-c, we conduct drive tests along the roads in the coverage area of the four AraMIMO-c BSes using a Nemo Handy UE [13]. For AraMIMO-tvws, we use AraMIMO-tvws UE at different locations, roughly 1.6 km apart. We use the maximum transmit powers for AraMIMO-c and AraMIMO-tvws BSes (i.e., 128 W and 10 W respectively). Measurement data from the field is analyzed using Laplace-equation-based, Physics-Informed Neural Network (PINN) [35] models. The models take the coordinates and throughput of the sample points to learn the coverage variability over space. The coverage map generated with PINN for AraMIMO-c is shown in Figure 9a, where yellow and green points indicate higher and medium capacity, respectively, while dark blue points represent limited-to-no coverage. The coverage grid is 19 km by 21.5 km and shows good coverage near the BSes. We observe varying capacity as we go farther from the BSes and zero coverage towards north-east due to blockage from terrain and residential areas. For AraMIMO-tvws, the coverage map is shown in Figure 9b where the size of the grid is 11.7 km by 14.4 km, a subset area of Figure 9a. The figure shows good coverage towards the south covering rural crop and livestock farms and grain mills etc. Some spots on the grid towards north and north-west are not covered due to blockage from residential buildings in the city, and the locations towards far-west have blind spots due to terrain and the angle of the UE from the BS sector antennas. A few locations towards east are also not covered due to severe blockage.

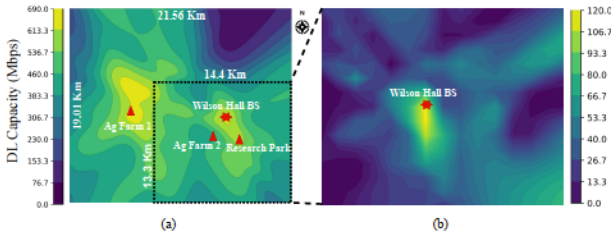


Figure 9: AraMIMO-c (a) and AraMIMO-tvws (b) Coverage map.

4.1.2 AraHaul Capacity

AraHaul features heterogeneous, long-distance wireless x-haul platforms across the microwave, mmWave, and free-space-optical frequency bands, enabling the use of spectral diversity for performance and robustness. In what follows, we use the 10.15 km long AraHaul link between the Ag Research Farm and Wilson Hall to characterize the AraHaul capacity and heterogeneity.

AraHaul-micro and AraHaul-mm Link Capacity. Out of the three bands, the most robust one is the microwave band

at 11 GHz.

We observe a link throughput as high as 892 Mbps (i.e., 96.4% of the theoretical limit of 925 Mbps) thanks to the robust nature of wireless communications at the microwave band. In comparison, the mmWave band at 80 GHz is more sensitive and susceptible to weather. While the theoretical limit of the mmWave link throughput is 10 Gbps, the highest throughput observed in our experiments is 6.96 Gbps, as shown in Table 3.

Table 3: AraHaul-micro and AraHaul-mm Link Capacity

Link	Freq. (GHz)	BW (MHz)	Mod. (QAM)	Tx-Power (dBm)	Antenna Gain (dBi)	Beam-Width	Achieved Capacity
AraHaul-micro	11	100	4096	26	33.6	3.2°	892 Mbps
AraHaul-mm	80	2000	32	13	50	0.5°	6.96 Gbps

AraHaul-fso Link Capacity. AraHaul-fso is a terrestrial long-distance FSO link uniquely available in ARA. We observe in our field measurement that AraHaul-fso transceivers can attain a peak reception power of -6.86 dBm, which is about 17 dB above the receiver sensitivity of -24 dBm, allowing for a maximum communication capacity of 10 Gbps per signal branch and 160 Gbps aggregate capacity with 16 signal branches. Our AraHaul-fso APIs allow researchers to measure, for the first time, the scintillation effect and weather impact on such terrestrial long-distance FSO links in real-world settings, and they enable experimentation with FSO systems and protocol designs. Refer to Section 4.2.3 for example studies.

4.2 Example Rural Wireless Experiments

In what follows, we demonstrate three example wireless experiments with AraSDR, AraMIMO-tvws, and AraHaul. Other example experiments with weather measurement, spectrum sensing, and power consumption characterization can be found in the Appendix.

4.2.1 Communication Delay Analytics Using SDRs and Open-Source 5G Platforms

ARA uses fully programmable USRP SDRs N320 and B210 at the BSes and UEs, respectively. Together with open-source 5G platforms such as OpenAirInterface5G, these SDRs enable deep insight into the system behavior. For instance, one open challenge in 5G and 6G is how to enable real-time cyber-physical systems that require data be delivered by their deadlines. One important step toward meeting such requirements is to understand the sources of delays. To this end, ARA’s field-deployed, fully-programmable SDRs enable collection of fine-grained delay data for packets traversing the 5G network stack using the OpenAirInterface5G software platform.

More specifically, using the OpenAirInterface5G (OAI5G) [7] software stack and LatSeq [37] (a low-impact internal delay measurement tool for OAI5G), we extend LatSeq to

Table 4: Mean layer contributions of total packet latencies

	Average delay (msec) $\pm$ CI(95%)	
	Rain	No Rain
SDAP	0.00391 $\pm$ 0.00115	0.00355 $\pm$ 0.00029
PDCP	0.00690 $\pm$ 0.00017	0.00712 $\pm$ 0.00016
RLC	30.0579 $\pm$ 0.28633	7.63437 $\pm$ 0.11103
MAC	0.16896 $\pm$ 0.00010	0.08133 $\pm$ 0.00014
PHY	0.01896 $\pm$ 0.00108	0.01784 $\pm$ 0.00111

capture, store, and analyze the internal delays of packets between UEs and gNBs for both uplinks and downlinks. We insert measurement points across the whole OAI5G network stack from the application layer to the physical layer. The measurement data include timestamps of packets entering and exiting each layer. These data are crucial in rebuilding the packet journey and estimating the per-layer contribution to the end-to-end delay of a packet.

For an outdoor SDR link whose length is 200 m, we leverage the ping utility tool to generate packets in both the uplink and downlink directions and collect the packet delay data in the form of .lseq logs from the gNB and UE. Given the significant impact of weather on wireless communications, we investigate the impact of weather on packet delays. In particular, we measure packet communication delay with and without rain. We use a channel bandwidth of 40 MHz, 6 downlink and 4 uplink OFDM symbols, 30 kHz subcarrier spacing, and 3586.40 MHz center frequency in this experiment.

Figure 10 shows the cumulative distribution function (CDF) of the delays of 100 packets generated using ping. Each packet is 100 KB in size and generated every 10 ms. It can be seen that, given a target delay bound of 10 ms, almost all packets meet this requirement in the absence of rain. However, with rain falling at an average rate of 2.06 inches per hour, only 70% of packets meet the delay bound.

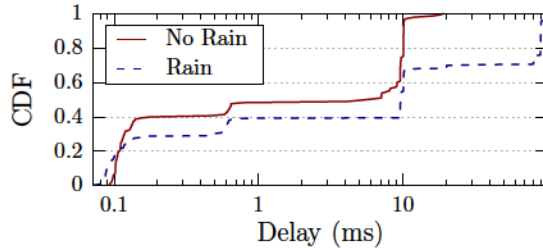


Figure 10: CDFs of packet delays in different weather

To understand the above behavior, we show in Table 4 the delays introduced by the individual layers of the 5G network stack. We see that the average delay introduced by the MAC layer doubled in the presence of rain. This is due to the increase in the number of packet re-transmissions during the rain. Another layer contributing to the large delay during rain is the Radio Link Control (RLC) layer. This is due to the use of lower-order modulation-and-coding-schemes during rain. Accordingly, much smaller Transport Block Sizes (TBS) are used, which in turn leads to more time spent in segmenting packets at the RLC layer and more MAC layer frames have to

be transmitted, resulting in longer delay. Such measurement insight helps suggest optimization strategies towards reducing communication delays, for instance, by increasing the number of scheduled physical-resource-blocks to increase the TBS at the RLC layer which in turn reduces segmentation.

Similarly, with the SDRs deployed in real-world outdoor rural settings in addition to a 50-node indoor sandbox, ARA serves as a first public O-RAN testbed for experiments tailored to rural and agriculture use cases [46].

4.2.2 User Grouping Experiment in TVWS mMIMO

Through its rich APIs for massive MIMO (mMIMO) control and measurement, AraMIMO-tvws enables unique experimental studies in the TVWS band at the PHY, MAC, and higher layers in rural settings.

As an example, we experimentally characterize the effect of the spatial distribution of UEs on the achievable capacity, Figure 11a shows the aggregate capacity achieved when different sets of UEs are connected to the BS. Set 0 includes all 7 UEs, while Set 1 to Set 5 have 4 different UEs each, as can be seen on the map and table in Figure 11a. Each UE has two RF chains connected to a cross-polarized directional antenna, hence supporting two spatial data streams. Multi-user MIMO (MU-MIMO) is employed by the BS to group multiple streams together. Maximum aggregate capacity of up to 400 Mbps is achieved with Set 0, where all 7 UEs (up to 14 spatial data streams) are connected to BS, and multiple sub-groups of streams are created and scheduled at different resource blocks (RBs). There is a total of 42 RBs, 540 kHz each, equivalent to 24 MHz bandwidth with guard bands.

Figure 11b shows how groups with different numbers of streams (n) are scheduled at each RB, where darker gray scales represent more frequent usage of the corresponding group. The group usage for Set 0 shows that the BS is able to group up to 8 streams (out of the 14 available) at each RB. For comparison purposes, we also include in Figure 11a the aggregate capacity achieved when forcing all streams to be grouped together – a non-optimal grouping strategy hence resulting in a lower capacity. Set 1 consists of UEs 1, 2, 5, and 6, as shown on the map in Figure 11a. This set of UEs achieve an aggregate capacity of 250 Mbps, which is lower than that achieved by Set 2 UEs (340 Mbps). The reason is that Set 2 UEs are more spatially separated while Set 1 UEs are packed in a smaller area. This effect is further illustrated in Figure 11b where the system can schedule groups with up to 8 streams for Set 0, 6 streams for Set 2 and up to 4 streams for Set 1 on most of the RBs.

In Figure 11c, we plot the orthogonality values between the channels associated with the grouped streams, which is calculated as one minus the multiple correlation coefficient between them. The figure shows that Set 2 UEs can achieve high orthogonality values with up to 6 streams, while for Set 1, if 6 or more streams are grouped together, the orthogonality

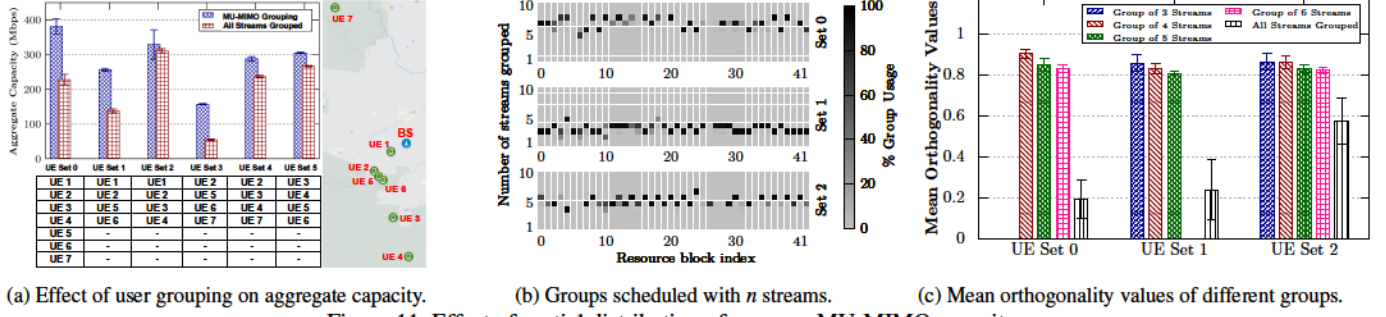


Figure 11: Effect of spatial distribution of users on MU-MIMO capacity.

value is very low and hence not recorded. We also observe that, when all streams are grouped together in each set, the orthogonality value of the Set 0 (with 14 streams) is the lowest, while Set 2 (with 8 streams) yields a higher orthogonality value than Set 1. This highlights the importance of having a proper grouping strategy for a given set of UEs in order to maximize the overall capacity.

In the above study, the default grouping strategy of the COTS application has been used. The AraMIMO-tvws APIs allow experimenters to perform other mMIMO experiments, for instance, those with specific sets of users, specific grouping strategies, or specific transmission strategies.

4.2.3 Long-Distance Wireless X-Haul Experiment

One key barrier to the real-world adoption of long-distance wireless x-haul communications is the weather impact on communication performance and robustness. Therefore, a critical need in long-distance rural wireless x-haul research is to characterize weather impact, whose insight will shed light on solution avenues. In what follows, we present example experiments characterizing weather impact on heterogeneous wireless x-haul platforms in ARA, in hope of sharing a glimpse into the broad research opportunities enabled by AraHaul.

AraHaul-micro and AraHaul-mm. AraHaul provides rich APIs for configuring and measuring AraHaul-micro and AraHaul-mm links through , standard NETCONF and SNMP protocols. Using these APIs, we measure the receiver-signal-strength (RSL) and throughput for the following link configurations: 1) *11 GHz AraHaul-micro link*: 100 MHz channel bandwidth, 4096 QAM modulation, and 26 dBm transmission power; 2) *80 GHz AraHaul-mm link config. #1*: 1 GHz, 16 QAM, and 14.5 dBm; 3) *80 GHz AraHaul-mm link config. #2*: 2 GHz, 32 QAM, and 13 dBm.

Figure 12 shows the link RSL and throughput under different rain rates. We see that the microwave link at 11 GHz is able to maintain steady RSL and throughput regardless of the rain condition. In contrast, the mmWave link at 80 GHz is more susceptible to weather; it yields a significantly higher throughput under no-rain and light-rain conditions, but its

performance deteriorates quickly when the rain rate increases. These results demonstrate the inherent tradeoff between communication capacity and weather resiliency across wireless x-haul links at different frequency bands, as well as the criticality of optimally controlling the operation parameters of higher-frequency x-haul links. They demonstrate the need for leveraging spatiotemporal diversity to enhance overall system robustness, whose study is enabled by mesh deployment of AraHaul; they also demonstrate the need for leveraging spectral diversity to optimize overall system throughput and robustness, whose study is enabled by the multi-frequency-band architecture of AraHaul.

AraHaul-fso. One major gap in existing long-distance terrestrial FSOC studies is the lack of real-world measurement data on weather impact, that is, scintillation effect introduced by atmospheric turbulence. Using the first-of-its-kind real-world AraHaul-fso deployment and open APIs, we investigate the FSOC scintillation effect by measuring the receiver-side avalanche-photodiode (APD) voltage levels and the average pixel values of the receiver CMOS camera output. Selected results are shown in Figure 13, where the temporal fluctuations of the APD voltage levels and pixel values over time can be clearly observed and precisely quantified. We also study how the scintillation effect varies under different rain conditions. As shown in Figure 14, the scintillation effect and losses become more severe under more intense rain conditions, and the impact can be precisely quantified too. Such measurement studies will serve as a solid foundation for future research

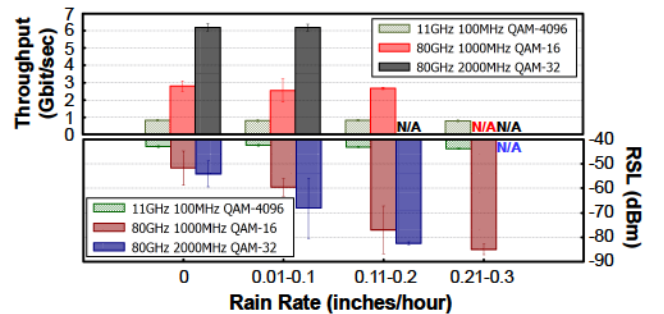


Figure 12: Impact of rain rate on AraHaul-micro and AraHaul-mm links (confidence interval = 95%).

explorations, for instance, detailed characterization of FSOC channels under different weather conditions, and development of predictive models for FSOC control.

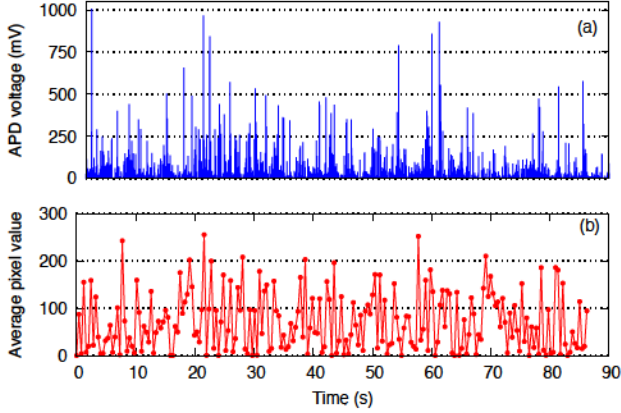


Figure 13: Example scintillation effect captured by the beacon receiver: (a) APD voltage over time; (b) average pixel value of the CMOS camera output over time.

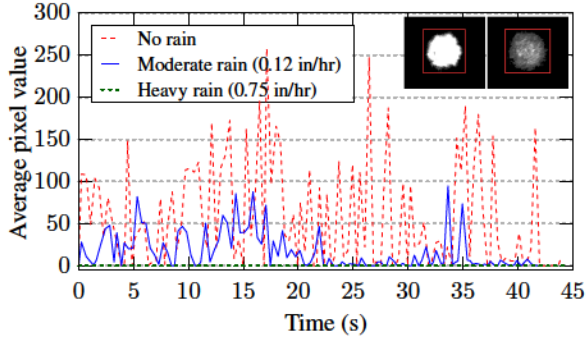


Figure 14: Comparison of the average pixel value (between 0 and 255) of CMOS camera output under different rain conditions. The spot diagrams located at the upper right corner show the distorted beams due to scintillation: left – no rain; right – moderate rain.

4.3 Example Rural Application Experiments

ARA is architected to support wireless and application co-evolution such as enabling higher-network-layer and application research in addition to experiments at the lower network layers as shown in Section 4.2. In what follows, we demonstrate experiments of an innovative wireless transport solution integrated with a real-time, high-resolution video streaming application service as required by agriculture automation.

Real-Time Liquid Wireless Transport. Agriculture automation (e.g., real-time data analytics and teleoperation [34]) requires high-throughput, low-latency communications in the presence of uncertainties in wireless communications. To

meet the demanding requirements, we implement a transport-layer solution called Liquid Transport Layer (LTL). LTL uses the state-of-the-art RaptorQ fountain code [30, 41] to improve network reliability while maintaining low latency by taking advantage of the *liquid* nature of RaptorQ encoded data (specifically, with key properties of expandability and interchangeability [22]). The liquid nature enables low-overhead, reliable, and real-time data delivery by eliminating the delay in traditional, retransmission-based schemes [34].

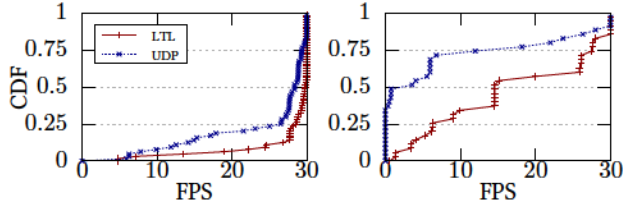
Experiment Setup. We place a UE on an ag vehicle. The UE is connected to a 360° camera on the vehicle, which live-streams 4K 360° video at a bit rate of 30 Mbps showcasing the potential of ARA to support high-throughput, real-time applications. The live video streaming is enabled by the GStreamer [42] multimedia framework, which is installed on the UE host computer. Using the GStreamer RTP plugin, the RTSP stream from the camera is pulled and sent to a streaming server in ARA's data center. The UE is equipped with an AraMIMO-c radio, which is connected to the Wilson Hall BS. The vehicle moves along a designated route across a farm field, which is about 2.63 km away from the BS. The speed of the vehicle is about 20 km/hour and each experimental trial takes about 110 seconds. We comparatively study the behavior of LTL and a baseline UDP solution without LTL.

QoE Metrics & Measurement Results. We evaluate the Quality of Experience (QoE) in video streaming in terms of the following metrics: 1) *Frames Per Second (FPS)*: number of frames per second decoded at the receiver, 2) *Structural Similarity Index Measure (SSIM)*: comparison of structural information between the source video and received video, and 3) *Stall Ratio*: percentage of time the receiver spends in waiting for new data to update the live stream compared to the entire duration of the stream.

Measurement results are shown in Figure 15 and Table 5. The *good connectivity* area is defined as the region where the UE has a stable and high-throughput connection with the BS, while the *bad connectivity* area refers to the edge of the cell with sporadic and unstable connectivity. As shown in Figure 15a, LTL yields a high FPS close to 30 in the good connectivity area, and provides a higher overall FPS than the baseline UDP solution. The improvement increases significantly as the UE moves away from the BS and gets closer to the edge of the cell, as shown in Figure 15b. Moreover, LTL demonstrates a similar or higher mean SSIM score and a lower mean stall ratio than the baseline UDP solution, particularly in the bad connectivity area, as shown in Table 5.

5 Related Work

While notable outdoor wireless testbeds exist worldwide, very few focus on rural and agriculture applications. In Japan,



(a) Good connectivity area

(b) Bad connectivity area

Figure 15: Comparison of CDF of FPS for LTL and UDP video streaming solutions at the bit rate of 30 Mbps.

Table 5: Comparison of SSIM Score and Stall Ratio (mean value $\pm$ 95% CI) for LTL and UDP solutions.

	Good Connectivity		Bad Connectivity	
	SSIM	Stall Ratio	SSIM	Stall Ratio
LTL	94.2% $\pm$ 0.3	3.8% $\pm$ 0.5	87.8% $\pm$ 0.3	41.8% $\pm$ 0.4
UDP	95.0% $\pm$ 0.2	4.6% $\pm$ 0.3	76.5% $\pm$ 0.2	58.6% $\pm$ 0.2

Niigata University has deployed a wireless mesh network testbed to address the digital divide in rural mountain areas [43]. In Finland, the Converged Infrastructure for Emerging Regions (CIER) project has developed a wireless mesh network testbed for robust, energy-efficient, and cost-effective heterogeneous wireless networking [38]. In UK, the 5G RuralFirst [10] testbed hosts a cloud core network and operates across an array of frequency bands including 700 MHz, 2.4 GHz, 3.5 GHz, 5 GHz, and 26 GHz. It facilitates experimentation across diverse use cases encompassing dynamic spectrum sharing, broadcast, agriculture, and industrial IoT. However, these testbeds do not support research in TVWS massive MIMO and long-distance, high-capacity x-haul, nor do they consider wireless and application co-evolution. 5G RuralFirst also does not have SDR systems, thus not supporting experiments in O-RAN and open-source NextG.

In Europe, the 5G testbed at University of Bristol [25] is a part of the BIO (Bristol is Open) city testbed, with a specific focus on smart city applications. The NITOS [33] testbed at University of Thessaly (Greece) has 50 nodes deployed on a building rooftop, supporting experiments with Wi-Fi, WiMAX, and LTE. However, they do not support experiments using SDRs, TVWS massive MIMO, and wireless x-haul systems, and NITOS does not support 5G experiments. In the realm of wireless x-haul, the Patras 5G testbed [44] hosts a private 5G network with a mmWave backhaul. However, it does not support experiments with multi-modal, long-distance, and high-capacity wireless x-haul systems, nor does it support TVWS massive MIMO research. ExPECA [32] is an edge computing and wireless communication research testbed located inside a unique isolated underground facility (20m below ground) in Sweden, and is equipped with compute resources and SDR nodes, enabling wireless experiments inside a highly controlled environment.

Most closely related to ARA are the wireless testbeds from the U.S. NSF Platforms for Advanced Wireless Research (PAWR) program [6], that is, COSMOS [36], POWDER [20], and AERPAW [31]. COSMOS and Powder are deployed in

the New York City and Salt Lake City respectively. COSMOS focuses on mmWave communications, and POWDER focuses on programmable wireless networks. They do not focus on rural broadband, nor do they support wireless and applications research using COTS 5G massive MIMO systems. AERPAW is deployed in Research Triangle, North Carolina, and it focuses on UAV wireless networking. The COTS 5G platform of AERPAW does not support massive MIMO. None of these testbeds support research experiments in TVWS massive MIMO nor long-distance, high-capacity wireless and free-space optical x-haul.

6 Concluding Remarks

Addressing the unique challenges and opportunities of rural broadband, ARA is a first-of-its-kind wireless living lab featuring the state-of-the-art wireless access and x-haul platforms, as well as high-performance compute resources embedded end-to-end from user equipment to base stations, edge, and cloud. ARA enables unique research experiments ranging from the modeling to the architectures, technologies, services, and applications of rural wireless systems, covering a wide range of topics such as those in O-RAN, open-source NextG, TVWS massive MIMO, spectrum innovation, integrated rural wireless access and x-haul, 360° video streaming, real-time edge data analytics, and agriculture automation. ARA enables wireless and application co-evolution through a testbed architecture that integrates fully-programmable SDR and configurable COTS platforms. One open challenge for future research is developing open-source NextG hardware and software platforms that meet stringent performance and robustness demands by real-world applications. Leveraging ARA's support for research reproducibility and community collaboration, another area worthy pursuing is using ARA as a tool for building collaborative communities to address grand challenges in advanced wireless and rural broadband (e.g., predictable real-time wireless networking for safety-critical cyber-physical systems).

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Appendix

In the Appendix, we include the details of three more example wireless experiments enabled by the ARA platform, in addition to the ones described in Section 4.2.

A Weather Experiments

ARA is unique in its capability of enabling advanced experiments to study the impact of weather on wireless communication systems. To provision the weather data, ARA is equipped with high-precision weather sensors and disdrometers to capture fine-grained variations in weather conditions such as precipitation type (rainy, snowy, foggy, or drizzling), rain drop size and velocity distribution, wind speed and direction, humidity, temperature, and atmospheric pressure. With the weather data, ARA offers a new dimension to the wireless research to unravel the possible hidden correlation between the weather conditions and the wireless system performance. Such a study is critical in analyzing the performance of ARA-RAN and ARA-haul links, especially the free space optical link, which has significant dependence on atmospheric conditions. Besides predicting the weather, the radio parameters can be tuned based on the anticipated weather conditions to

achieve optimum performance. Figure 16 shows an example of the temporal and spatial variation of rain rate collected from two BS sites. The spatial diversity of weather conditions indicates the possibility of location-based tuning of the device attributes considering the weather condition at the location. We demonstrate the influence of rain on the ARA-RAN and ARA-Haul performance in Section 4.2.1 and Section 4.2.3, respectively. A more detailed study on rural wireless channel measurements can be found in [47].

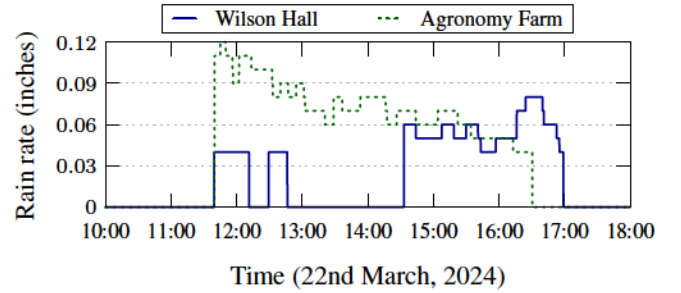


Figure 16: Example temporal and spatial variation of rain rate collected in ARA.

B Spectrum Sensing Experiment

RF spectrum is fundamental to wireless communication systems, acting as their lifeblood. ARA has deployed Keysight’s RF sensors at BS sites and NI’s SDRs at UE stations to capture the spatio-temporal dynamics of RF spectrum within the region. One interesting spectrum that is worth in-depth investigation is the TV White Space (TVWS) spectrum from 470 to 698 MHz. The primary users of this spectrum band are the TV broadcasters and the unlicensed microphones that transmit in this band. It is well-known that the majority of the TVWS is unoccupied or unused for most of the time, which is especially true in rural regions. Therefore, there are abundant opportunities for secondary users to utilize the TVWS spectrum. In order to do so, it is critical to have a thorough understanding of the usage pattern of the primary users, both temporally and spatially. We have developed APIs that allow users to collect and study the usage of the TVWS spectrum near the ARA footprint.

An example collection of TVWS usage data is plotted in Figure 17, where the dynamic behavior of the primary user’s transmission activity vividly portrays the spectrum’s fluctuating nature. Here, the x-axis denotes the indices of broadcast TV channels where each channel is 6 MHz wide, and the span ranges from 470 MHz to 698 MHz, while the y-axis represents the temporal occupancy of these TV channels for the monitoring time period of 15 minutes where each time slot is one second long. In addition, the color intensity of each slot represents the received signal strength captured at the monitoring node ranging from -20 to -120 dBm.

Table 6: Equipment level power consumption of Residence Hall BS averaged over 1 month

		AraMIMO-tvws	AraSDR	Compute	Switches	AraHaul-fso	Other	Total
Value	Amps	5.822	4.377	2.699	2.332	1.392	0.783	17.405
	Watts	692.234	415.198	319.516	188.118	115.482	45.173	1775.721
Percentage	Amps	33.451%	25.149%	15.508%	13.395%	7.997%	4.500%	100%
	Watts	38.983%	23.382%	17.994%	10.594%	6.503%	2.544%	100%

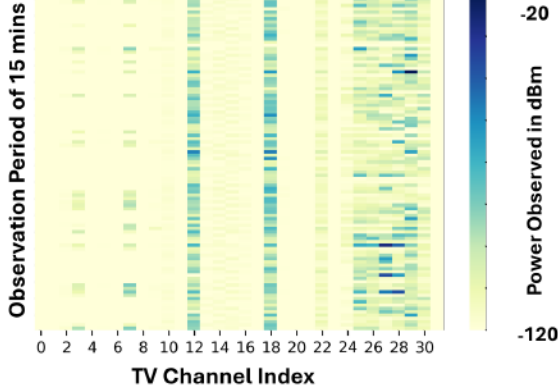


Figure 17: Example TVWS usage near the ARA footprint.

We have a couple of observations from the captured data. First, as many as 15 TV channels are available near the ARA footprint. This available spectrum may be used by small-scale Internet Service Providers (ISPs) or Mobile Network Operators (MNOs) to provide a better wireless coverage in rural areas. In addition, it also may be used by farmers to deploy their own IoT networks to help produce better agricultural yield. Second, the available spectrum in the TVWS is highly fragmented, varying drastically over both time and space, which calls for innovative solutions for better spectrum modeling, management, utilization, and sharing.

With ARA, users can use the provided APIs to run spectrum sensing experiments to study the spectrum of their interest and collect spectrum data at desired time and location. Captured spectrum data can be used to model the spatio-temporal dynamics of the spectrum occupancy and channel behaviors [40]. These models serve as valuable resources for the development of spectrum sharing or co-existence protocols and systems, which can then be evaluated on ARA.

C Power Consumption Experiment

Characterizing power consumption is critical for today's cellular networks for realizing the concept of green communication. With smart power distribution units (PDUs), ARA provides monitoring and management APIs to characterize the power consumption profile of individual components in cellular networks. The APIs offer the following unique capabilities:

1. Real-time power consumption monitoring for individual components in all BSes;

2. Long-term power consumption data collection and storage in our database.

Figure 18 shows one such experiment where real-time power consumption pattern of the AraMIMO-tvws BS under different states is measured. The states of the BS include *no transmission*, *transmitting but idle*, *k number of UEs connected*, and *k number of UEs transmitting data*. The power consumption increases up to 21% from the first state (i.e., no transmission) to the last state (i.e., six UEs are connected and send data). There is a sudden decrease in power consumption when the BS start transmission which is attributed to restart of the components in individual RF chains in the frontend to make the BS ready for transmission.

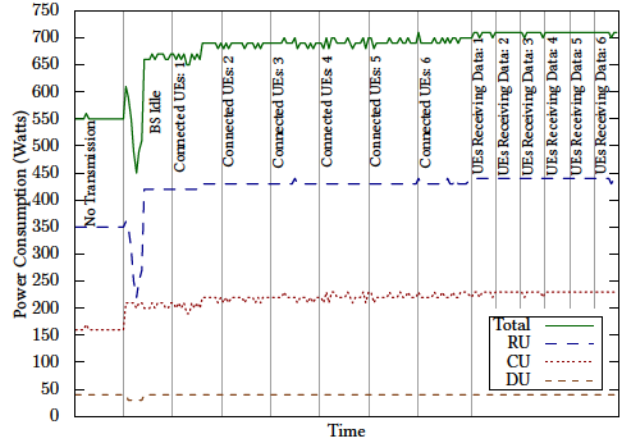


Figure 18: Power consumption of AraMIMO-tvws BS in different States.

The long-term data collection capability allows analysis and modeling of power consumption over time. Table 6 shows the power consumption (actual values and percentage) of individual components at Residence Hall BS over a period of one month. We can observe that AraMIMO-tvws has the most power consumption and AraHaul-fso switches has the least. Such a comprehensive view of the distribution of power utilization across different equipment helps in intelligently controlling the device ON/OFF times, thereby paving the path toward green communication.