AraSDR: End-to-End, Fully-Programmable Living Lab for 5G and Beyond

Joshua Ofori Boateng, Tianyi Zhang, Guoying Zu, Taimoor Ul Islam, Sarath Babu, Hongwei Zhang, and Daji Qiao
Department of Electrical and Computer Engineering, Iowa State University, USA
{jboateng, tianyiz, gyzu, tislam, sarath4, hongwei, daji}@iastate.edu

***Abstract*—Wireless innovation can significantly benefit from having access to real-world, over-the-air (OTA) living labs for open-source prototyping and field evaluation of emerging, state-of-the-art solutions. However, the existing open-source 5G testbeds are either confined to controlled indoor environments, or they use commercial-off-the-shelf (COTS) user equipment (UEs) only without supporting software-defined-radio (SDR) UEs, thus lacking real-world fidelity or end-to-end programmability from UEs to gNBs and core networks. To fill the gap, we develop and deploy AraSDR that, as an integral element of the ARA Platform for Advanced Wireless Research (PAWR) on rural broadband, serves as a first-of-its-kind outdoor living lab supporting end-to-end, fully-programmable 5G experiments with SDR UEs and base stations (BSes) in real-world rural settings. AraSDR deploys in agriculture farms and rural cities NI N320 and B210 as the BS and UE SDRs respectively, and it employs low-cost, performant custom RF front-ends with power amplifiers (PAs) and low-noise amplifiers (LNAs) to boost the transmit and receive signals for extended cellular coverage. To enable real-world SDR-based experiments with open-source 5G stand-alone (SA) TDD cellular operations, we address the challenges of reliable control signaling, precision timing of the transmission/reception mode of RF front-ends, as well as transmission and reception gain control. We develop the software control framework to support remote experiments with streamlined workflows and to enable container-based experiment portability and reproducibility. Using OpenAirInterface (OAI) as an example open-source 5G software platform, we demonstrate the capability of AraSDR in supporting real-world, OTA 5G experiments.**

***Index Terms*—ARA Wireless Living Lab, software defined radio, end-to-end programmability, open-source, 5G, OpenAirInterface**

I. Introduction

5G-and-beyond cellular networks strive to provide unprecedented capacity, ultra-high reliability, and ultra-low latency to support diverse applications. Unleashing their full potential necessitates collaborative effort involving innovation, open-source initiatives, as well as research and experimentation. Open source initiatives spearheaded by projects such as OpenAirInterface (OAI) [1] and srsRAN [2] are at the forefront of this transformation and are instrumental in democratizing the development and deployment of 5G networks and enabling whole-stack research and innovation. Leveraging OAI and srsRAN, experimenters can modify the software stacks, enabling in-depth exploration and experimentation with various 5G functionalities, including new algorithms, protocols, and network configurations, which are often not feasible with proprietary solutions.

While open-source 5G initiatives have made significant strides in research under indoor environments, building large-scale fully programmable 5G testbeds outdoors, running entirely on SDRs across base stations (BSes) and user equipment (UEs), remains crucial. Some of the key drivers for such testbeds include studying wireless channel characteristics under varying weather, terrain, and interference conditions, which are not feasible in any indoor setting. Moreover, experiments in outdoor environments provide more realistic validation of advanced wireless solutions, ensuring that they perform as expected in production systems. Provisioning such large-scale testbeds also enables whole-stack programmability ensuring the evaluation of emerging, state-of-the-art solutions in end-to-end, real-world network settings without being limited only to emulated or simulated settings.

As far as 5G-enabled testbeds are concerned, several outdoor and indoor platforms were designed with the aim of enabling repeatable and reproducible experiments. Among them, the well-known testbeds include POWDER [3], COSMOS [4], AERPAW [5], and data-driven mobile 5G testbed [6] in the United States. The platforms from Europe include Patras 5G [7], NITOS [8], and mMIMO testbed in BIO [9]. However, these platforms either do not emphasize open-source solutions or do not offer an end-to-end solution to the challenge of supporting open-source 5G software platforms in outdoor environments. Platforms such as POWDER support OAI and srsRAN, but they currently rely on commercial-off-the-shelf (COTS) UEs, thus unable to provide whole-stack programmability at UEs and unable to support fully-programmable end-to-end 5G-and-beyond experiments across UEs, BSes, and core networks.

To fill the gap, we develop and deploy AraSDR to serve as a first-of-its-kind at-scale outdoor living lab supporting end-to-end, fully-programmable 5G experiments with SDR UEs and BSes in real-world rural settings. As an integral element of the ARA Platform for Advanced Wireless Research (PAWR) [10] which focuses on rural broadband and spans an area of diameter over 30 km, AraSDR deploys in agriculture farms and rural cities NI N320 and B210 as the BS and UE SDRs, respectively, and it employs low-cost, performant custom RF front-ends with power amplifiers (PAs) and low-noise amplifiers (LNAs) to boost the transmit and receive signals for extended cellular coverage. AraSDR deploys 5G core networks in high-performance compute nodes of ARA in the Iowa State University (ISU) data center, and they are connected to the

BSes via high-speed fiber and wireless backhaul networks. Our key contributions in this work are as follows:

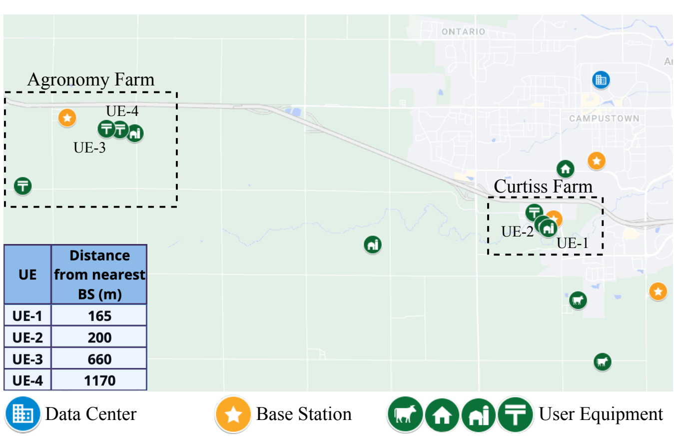
1) To the best of our knowledge, AraSDR is the first-ever at-scale outdoor living lab supporting 5G standalone (SA) TDD mode and end-to-end, whole-stack programmability across UEs, BSes, and core networks.
2) To enable real-world SDR-based experiments with open-source 5G SA TDD cellular operations, we address the challenges of reliable control signaling, precision timing of the transmission/reception mode of RF front-ends, as well as transmission and reception gain control.
3) We perform a detailed performance comparison between the outdoor deployment of OAI 5G and the corresponding indoor sandbox. We demonstrate that employing RF front-ends enables better performance outdoors in terms of coverage and throughput.
4) We containerize the OAI 5G software platform to run end-to-end open-source 5G networks from UEs to BSes and core networks, ensuring isolation, portability, and reproducibility of experiments. The custom pre-built containers are made publicly available.

II. Infrastructure Design and Deployment

In this section, we provide an in-depth view of the design and implementation of AraSDR. First, we highlight the overall deployment including the spatial distribution of BS and UE nodes and the end-to-end design details from UE to the 5G core. We emphasize on the design of AraSDR in ensuring robust connectivity to support reproducible experiments using open-source 5G protocol stacks.

A. AraSDR Deployment

Fig. 1 shows the Phase-1 deployment of AraSDR. Currently, there are four software-defined radio (SDR) base stations deployed throughout the City of Ames in Iowa, where the Iowa State University (ISU) resides while three more BSes will be added in Phase-2 by May 2024. The current deployment covers a diameter of approximately 15 km while the whole deployment after Phase-2 will span a wide area of 30 km in diameter across central Iowa. There are 10 fixed-location UEs deployed in the coverage area of the BSes to support whole-stack 5G research. Each base station cell has at least two UEs within its footprint and is connected back to the data center where the 5G core resides via a fiber or wireless backhaul network. Mobile UEs on buses, fire commander vehicles, and agriculture vehicles are being deployed and will be available by early 2024 to support 5G research and experimentation in dynamic, mobile environments.

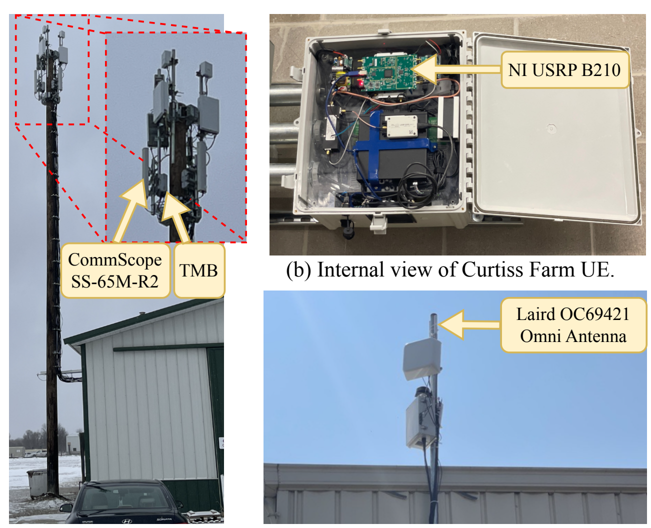


UE	Distance from nearest BS (m)
UE-1	165
UE-2	200
UE-3	660
UE-4	1170

Fig. 1: AraSDR Phase-1 deployment map. The table shows the distance of UEs from the nearest BS. The dashed-rectangles show the experiment location.

B. Base Station Design

The BS features a high-performance Dell R750 server as the baseband processing unit running the OAI 5G stack. The server meets the minimum requirement to run open-source 5G protocol stacks, and is also able to handle the complex processing tasks associated with 5G networks, such as massive MIMO beamforming, channel coding, and real-time signal processing. The NI N320 SDR [11] serves as the radio transceiver in the AraSDR BS design. N320 offers two receive (RX) and two transmit (TX) channels, all within a compact half-wide rack unit (RU) form factor. Each channel offers an instantaneous bandwidth up to 200 MHz, effectively covering an extended frequency range 3 MHz–6 GHz for high-bandwidth experimentation. In addition, N320 is equipped with a user-programmable FPGA for real-time, low-latency processing. For high throughput IQ streaming, we use the 10 Gbps SFP+ ports and a high-speed single-mode fiber to connect the SDR to the host server. To maintain the signal strength over a distance of 50 feet between the SDR and the RF frontend, we use the low-attenuation AVA5-50 cables to connect the N320 SDR to the tower mounted booster (TMB), which includes a power amplifier (PA) and a low noise amplifier (LNA). The CommScope SS-65M-R2 [12] sector antenna is deployed as the antenna element for the BS. Fig. 2(a) shows a picture of one of our deployed BSes at ISU's Curtiss Farm.



(a) Curtiss Farm BS. (b) Internal view of Curtiss Farm UE. (c) Curtiss Farm UE antenna mount.

Fig. 2: AraSDR BS and UE deployment at Curtiss Farm.

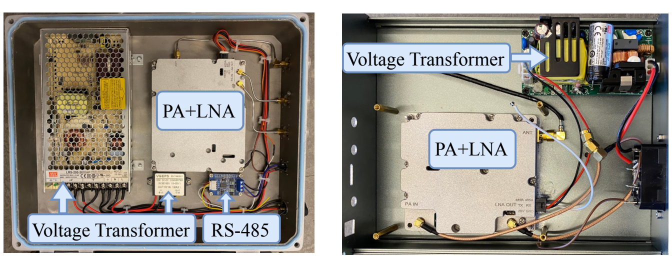
C. User Equipment Design

At the UE side, AraSDR uses the NI USRP B210, which offers up to 56 MHz of real-time bandwidth, an open and programmable Spartan™ 6 FPGA, and a USB 3.0 interface with adequate bus-power. The open-source 5G stack runs on a Supermicro SYS-E300-12D-8CN6P that serves as the UE host computer for B210. The B210 SDR also connects to a UE booster (UEB) consisting of a PA and an LNA to boost the signal level for better outdoor connectivity. The UEB connects to a single Laird OC69421 antenna via a 16 feet low-attenuation and flexible LMR-400 coaxial cable.

Besides the components of UE, the choice of enclosure is critical in outdoor deployments to protect the UE from environmental factors such as moisture, dust, and temperature variations. Therefore, we use an IP67-rated enclosure made from polycarbonate material, which is known for its durability and resistance to the above-mentioned environmental factors. Snapshots of our field-deployed UE at the Curtiss Farm location are shown in Figs. 2(b) and 2(c).

D. Power Amplifier and Low Noise Amplifier

The SDRs are primarily designed for short-distance indoor applications, i.e., they exhibit sub-optimal performance when used in outdoor environments. Therefore, for outdoor use, we employ two additional key components: (1) the TMB for the BS, and (2) the UEB for the UE. Both TMB and UEB are equipped with adjustable PA for amplifying TX signals, an LNA for amplifying RX signals, and a voltage transformer. Internal views of TMB and UEB are shown in Fig. 3. It is important to note that the TX and RX ports of the SDR are connected separately to the PA and LNA. In a time-division duplex (TDD) system using a single antenna, the booster includes a single port for the antenna and relies on a general-purpose input/output (GPIO) signal from the SDR to manage the TX-RX switching.



(a) TMB. (b) UEB.

Fig. 3: Internal view of TMB and UEB.

The TMB is enclosed in a waterproof casing mounted on the tower protecting it from weather impact, approximately 50 feet away from the SDR that is positioned inside the ground cabinet. To safeguard the control signal, the TMB utilizes RS-485 modules on both SDR and TMB sides. Since we prioritize portability, the UEB is mounted inside the UE enclosure. TABLE I lists the specifications of TMB and UEB. It is worth noting that the dimensions and weights listed in the table take into account the protective casing.

TABLE I: TMB and UEB specifications.

Specification	TMB	UEB
Frequency (MHz)	3400–3600	3400–3600
Maximum PA gain (dB)	51	43
Maximum LNA gain (dB)	25	25
Maximum Output Power (dBm)	40	31
Working bandwidth (MHz)	100	100
Noise figure (dB)	$\leqslant 2$	$\leqslant 2$
Dimensions (mm)	370×295×152	100×90×22
Weight (Kg)	8	0.5

III. Software Control Framework and 5G Software Platform

In this section, we present the software control framework for AraSDR and discuss the current support for the open-source 5G software platform OpenAirInterface (OAI).

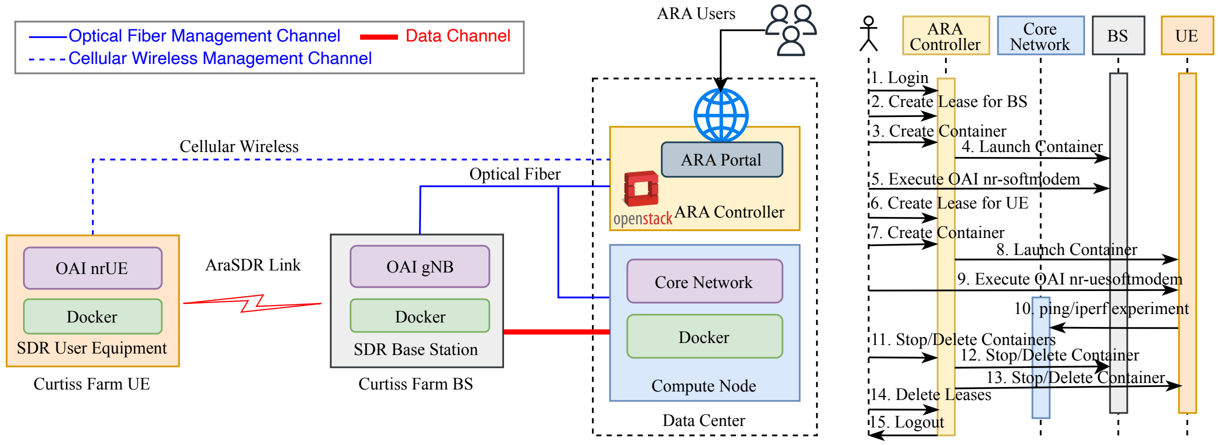
A. Software Control Framework

The software framework of AraSDR is a resource orchestration framework developed from the OpenStack cloud operating system, and it allows users to reserve compute and wireless resources to execute their 5G experiments. The framework offers container-based resource provisioning and, therefore, we provide pre-built containers for running open-source 5G BS, UE, and the core network. Fig. 4(a) shows the architecture of AraSDR software framework in the context of user experiments. For managing the resources, the AraSDR controller communicates with other nodes via the management channel, denoted as the blue dotted line in Fig. 4(a), while the data channel is used for carrying the user data. The 5G core network runs on the compute node in the data center. The ARA platform is made available to the research community for advanced wireless experiments via ARA web-portal up on registration [13].

Each BS site is equipped with a compute server hosting three SDRs. The server runs Docker daemon for enabling experiment containers on the host. Fig. 4(b) shows the workflow of the AraSDR experiment OAI 5G protocol stack. The user logs into the AraSDR portal, creates a reservation for a particular BS host compute node (in our case, the Curtiss Farm/Agronomy Farm BS as shown in Fig. 1), and launches a pre-built container equipped with OAI gNB on the reserved node. The same procedure is repeated for the UE node (in our case, the Curtiss Farm/Agronomy Farm UE). Both UE and gNB are configured and run to establish a wireless link between them. Further, we use *ping* and *iPerf* to verify the connection, i.e., to check the latency and throughput toward the 5G core. The container is stopped and deleted from the reserved node on the completion of the experiment. The reservation is deleted to make the resources available for other experimenters.

B. OpenAirInterface 5G Software Platform

In our experiments, we use OpenAirInterface (OAI) [14] as the open-source 5G software platform. Our choice of the 5G software is influenced by the support for end-to-end whole-stack research using both gNB and nrUE software components, which can be modified by experimenters. At the moment of



(a) AraSDR software architecture. (b) AraSDR experiment workflow.

Fig. 4: AraSDR software architecture for the OAI experiment in Curtiss Farm.

writing this paper, OAI is the only open-source software stack providing gNB and nrUE for n78 band TDD that the ARA platform is designed to support. We deploy both gNB and nrUE in Docker containers as mentioned in Section III-A. The containerization enables reproducibility of experiments and flexibility for experimenters to try their own pre-built Docker container images.

IV. Challenges and Lessons Learned

In this section, we discuss the challenges faced and the valuable lessons learned in designing and deploying AraSDR. We unfold the reasons behind the challenges and share our approaches in addressing them.

A. *Reliable Control Signaling between TMBs and SDRs*

At each BS site, the servers and SDRs are deployed in the cabinets mounted at the ground or at the rooftop, while the TMBs and antennas are usually mounted away from the cabinets and are atop a wireless tower/pole or on a rooftop structure. Placing SDRs close to the TMBs and antennas (e.g., atop a wireless tower) would require sturdy outdoor casing and high deployment and maintenance cost. In addition, the servers and SDRs are not designed for outdoor environments, thus they need to be deployed inside cabinets with good heating and air conditioning systems.

While the AraSDR BS deployment design allows convenience in site maintenance and operation as well as hardware and software troubleshooting, it introduces challenges due to the long distance between TMBs and SDRs. While the TMB can compensate for the signal loss incurred from the long cables connecting itself with the TX and RX ports of the corresponding SDR, it cannot amplify the control signal required to govern the operations of the TMB itself. SDRs use their GPIO ports to transmit control signals using a high voltage of 3.3 V and a low voltage of 0 V. However, due to power loss along control signaling cables, the high voltage can drop below 3 V at the receiver end. To deal with this issue, we use RS-485 modules to transmit control signals between TMBs and SDRs, thus ensuring reliable control signaling over long distances. RS-485 is an industry-standard protocol capable of reliable communication over distances up to 1.2 km.

B. *Precision Timing of TDD Transmission/Reception Mode*

In 5G TDD systems, TMBs and UEBs operate in the half-duplex mode. They need to be in the *transmission* mode whenever the corresponding BSes/UEs transmit data; otherwise, they should be in the *reception* mode. To ensure reliable communications, it is critical that the transmission/reception mode of TMBs/UEBs are precisely synchronized with data transmissions/receptions at the corresponding BSes/UEs.

Given how TMBs/UEBs are connected to the BS/UE SDRs, the transmission/reception mode of TMBs/UEBs is controlled by the voltage level of the SDR GPIO ports, with high voltage for the *transmission* mode and low voltage for the *reception mode*. In the OAI 5G protocol stack running on AraSDR, the function `set_gpio_attr()` in the `usrp_lib.cpp` software module is used to control the voltage level of GPIO ports. However, we find that the timing of the voltage levels of GPIO ports cannot be controlled precisely through the function in 5G TDD. Unlike in the LTE TDD mode where each time slot contains either all uplink (UL) or all downlink (DL) symbols, the frame structure of 5G NR allows the coexistence of UL and DL symbols within a single time slot. Through the OAI function `set_gpio_attr()`, the GPIO ports of a BS/UE maintain high voltage for an entire time-slot as long as there exists a single transmission symbol in that slot. For instance, the default setting of OAI 5G employs a 5 ms periodicity, comprising seven DL time slots, two UL time slots, and one mixed time slot, where the mixed time slot contains six DL symbols, four UL symbols, and four empty symbols as the guard time. Therefore, the control signal for the UEs should maintain a high voltage for two UL time slots and four UL symbols within each period. However, as depicted in Fig. 5, the high voltage of the out-of-sync control signal persists for three full time slots, thereby making the LNA of UEB inactive at the start of reception, four symbols after the completion of transmission.

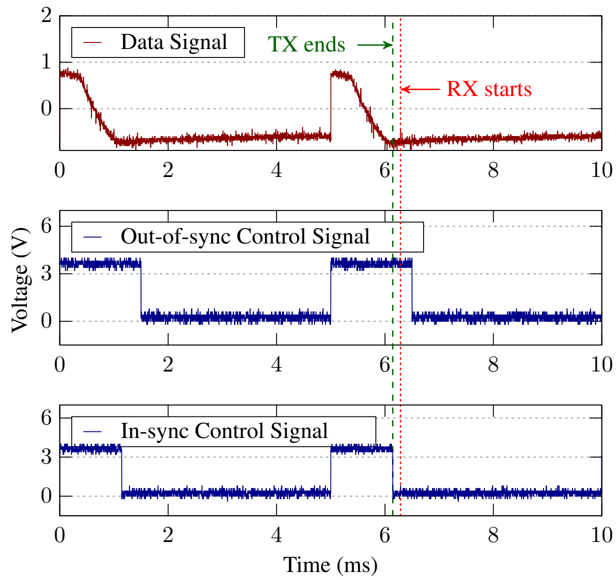


Fig. 5: GPIO synchronization at UEB, with each time slot being 0.5 ms.

To address the above issue, we modify the GPIO control program to precisely time the voltage level control via the USRP hardware driver (UHD) API `set_command_time()`. More specifically, we leverage the knowledge of the exact timing of the transmission of the first symbol of each transmission to synchronize the voltage change at the corresponding GPIO port. Similarly, based on the configured periodicity, we use high precision timing to trigger the setting of the GPIO port voltage to be low immediately after the transmission of the last symbol. Fig. 5 shows the data signal, the problematic out-of-sync control signal, and the in-sync control signal produced by our solution. Unlike the out-of-sync control signal where the high voltage persists for 1.5 ms (i.e., three time slots), the in-sync control signal ensures that the high voltage only lasts approximately 1.143 ms (two time slots and four symbols), effectively covering the entire transmission process without affecting the reception.

C. Transmission and Reception Gain Control

The OAI 5G implementation is highly sensitive to signal strength, and its performance varies with the configured gain. To understand the most appropriate configuration for the outdoor deployment involving PAs and LNAs, we demonstrate the impact of base station transmission and reception attenuations on the OAI channel quality using the channel quality indicator (CQI). In Fig. 6 we observe that, increasing attenuation on the TX chain leads to a drastic reduction in CQI to zero within the observation window and a subsequent link disconnection. However, increasing the attenuation on the RX chain maintains relatively better channel quality with CQI between 15 and 8. Therefore, in order to achieve better channel quality and link stability, it is appropriate to tune the reception attenuation instead of the transmitter attenuation.

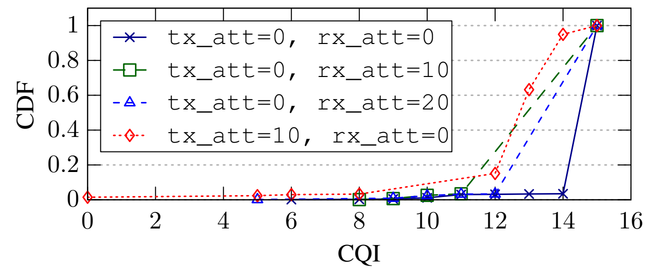


Fig. 6: CQI variation for different attenuation levels.

V. Performance Evaluation

The deployment of outdoor open-source 5G networks presents a unique set of challenges and opportunities, specifically when compared to their indoor counterparts. In this section, we present the key findings on the performance of OAI 5G on AraSDR deployment and compare it to an indoor deployed OAI 5G stack. We also present the quality of the AraSDR wireless links in terms of SINR at different outdoor UE locations.

A. Experimental Setup

We consider the BS and UE nodes at Curtiss Farm and Agronomy Farm, highlighted in Fig. 1, for our outdoor experiments. For comparing the performance, we use an indoor setup involving BS and UE separated by a distance of 2 m. TABLE II shows the specifications of the components used for both setups. The OAI core network runs on another Dell R750 server in the ISU data center and connected to the gNB via a fiber backhaul network. The outdoor setup uses a CommScope SS-65M-R2 antenna at the BS and a Laird Omnidirectional antenna at the UE, while the sandbox uses Panaroma PWB-BC3G-38-RSMAP omnidirectional antennas. The antennas operate in band78 TDD frequencies and the indoor setup does not include any RF amplifiers. TABLE III highlights the configuration parameters of gNB as well as nrUE which were used in both indoor and outdoor setups.

TABLE II: Experiment components and specifications.

	Component	Specification
BS	Server	Dell R750 Intel Xeon@3.6 GHz, 64 GB RAM, 16 Cores (32 Threads)
	TMB	Refer TABLE I
	Radio	NI USRP N320
	Transceiver	10G SFP+
UE	Server	Supermicro SYS-E300-12D-8CN6P Intel Xeon@2.7 GHz, 32 GB RAM, 8 Cores (32 Threads)
	Radio	NI USRP B210 with USB 3.0
	UEB	Refer TABLE I

TABLE III: Configuration parameters for gNB and nrUE.

	Parameter	Value
gNB	Duplex Mode	TDD
	Bandwidth	106 PRBs
	Center Frequency	3590.4 MHz
	Subcarrier Spacing	30 KHz
	TX Attenuation	0 dB
	RX Attenuation	10 dB
	Antenna Height	18.2 m
nrUE	TX Gain	66 dBi
	Antenna Height	9.1 m
	RX Gain	89.75 dBi

B. Throughput, Latency, and SINR

In Fig. 7, we show the cumulative distribution function (CDF) of the UDP downlink throughput samples from OAI for both outdoor and indoor setups measured using *iPerf*. The throughput observed in the outdoor setup was relatively higher than the indoor setup. For instance, the maximum achievable DL throughput for the outdoor scenario is 34.7 Mbps compared to 29.3 Mbps at indoors. The difference is due to the higher signal strength and SINR at outdoors from the use of RF amplifiers. Further, we evaluate the communication latency in terms of round-trip time (RTT) between nrUE and OAI core network for both setups using the *ping* utility. Fig. 8 shows the CDF of RTT samples. In Fig. 8, the RTT which was observed indoors is almost the same as the RTT observed in the outdoor deployment even though the UEs outdoors are located far from their nearest BS.

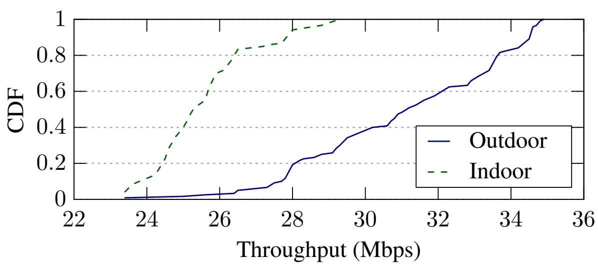


Fig. 7: UDP DL throughput for outdoor and indoor settings.

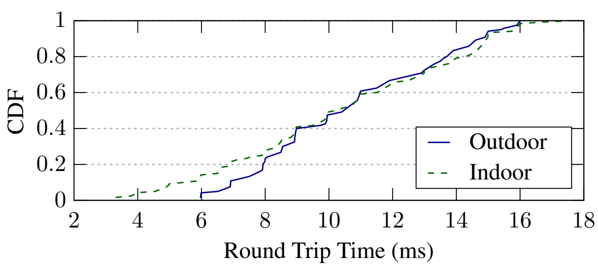


Fig. 8: Round-trip time for outdoor and indoor settings.

As far as the signal-to-interference-plus-noise-ratio (SINR) is concerned, we compare the measurements from UEs at both Curtiss and Agronomy farms. From Fig. 9, it is clear that UE-3 offers higher SINR than UE-4 due to UE-3's close proximity to the nearest BS. UE-2 provides higher SINR compared to UE-1 due to the fact that UE-1 is located in non line-of-light (nLoS) with the BS.

VI. Concluding Remarks

We developed and deployed AraSDR which, as an integral element of the ARA PAWR platform, provides an end-to-end, fully-programmable living lab for experimentation with 5G-and-beyond solutions in real-world rural settings. AraSDR features SDRs at both base stations and UEs, TDD RF front-ends, effective integration of the open-source 5G software platform OpenAirInterface, as well as a software control framework enabling reproducible, real-world 5G-and-beyond experiments. Future work will focus on extending AraSDR to support open-source 5G software platforms other than OAI

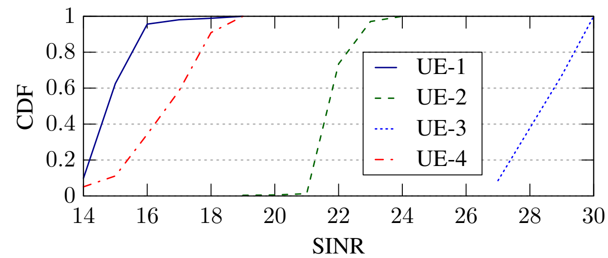


Fig. 9: SINR variation for different UE locations.

(e.g., srsRAN), using more BSes and UEs to study system capacity and coverage, and integrating Open RAN (O-RAN) software platforms.

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