Arena: A 64-antenna SDR-based Ceiling Grid Testbed for Sub-6 GHz Radio Spectrum Research

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ABSTRACT

Arena is an open-access wireless testing platform based on a grid of antennas mounted on the ceiling of a large office-space environment. Each antenna is connected to programmable software-defined radios enabling sub-6 GHz 5G-and-beyond spectrum research. With 12 computational servers, 24 software defined radios synchronized at the symbol level, and a total of 64 antennas, Arena provides the computational power and the scale to foster new technology development in some of the most crowded spectrum bands.

Arena is based on a clean three-tier design, where the servers and the software defined radios are housed in a double rack in a dedicated room, while the antennas are hung off the ceiling of a 2240 square feet office space and cabled to the radios through 100 ft long cables. This ensures a reconfigurable, scalable, and repeatable real-time experimental evaluation in a real wireless indoor environment. This article introduces for the first time architecture, capabilities, and system design choices of Arena, and provide details of the software and hardware implementation of the different testbed components. Finally, we showcase some of the capabilities of Arena in providing a testing ground for key wireless technologies, including synchronized MIMO transmission schemes, multi-hop ad hoc networking, multi-cell LTE networks, and spectrum sensing for cognitive radio.

KEYWORDS

Software-defined Radios, Wireless Testbed, Spectrum Research, Antenna Grid, Internet of Things.

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1 INTRODUCTION

The evolution of wireless networked systems continues to be a crucial commercial, strategic, and geopolitical matter. According to the latest Ericsson mobility report, there are now 5.7 billion mobile broadband subscriptions worldwide, generating more than 130 exabytes per month of wireless traffic. Moreover, it is expected that by 2020, over 50 billion devices will be absorbed into the Internet, generating a global network of "things" of dimensions never seen before—and growing at a compound annual growth rate (CAGR) of 27%. Industrial automation, smart cities, and distributed robotic systems will increasingly rely on large-scale wireless networked systems. In addition to their commercial strategic need, 5G and IoT have been identified as critical technologies for national security. Thus, wireless systems will continue to change the way we live, work, manufacture goods, and fight wars.

It is therefore to some extent surprising that the wireless research community is still lacking experimental facilities to support a "science" of rigorous and repeatable experimental evaluation of wireless networked systems—beyond simulation tools and small-scale, ad hoc, testbeds. The recent NSF Platforms for Advanced Wireless Research (PAWR) program is attempting to address this by developing four city-scale platforms for advanced wireless research to experiment with new IoT and wireless systems in outdoor "out-in-the-wild" environments. Similarly, Colosseum [4], once transitioned from the DARPA Specrtum Collaboration Challenge to Northeastern University, will provide a *shared* wireless network emulation facility to experiment and test *at scale*, in a fully *controlled and observable environment*, and with *hardware in the loop*. While the availability of PAWR platforms and Colosseum is expected to be a major stepping stone toward the goal of open rigorous experimentation with shared facilities, the community is still lacking a platform to test at scale medium- and short-range radio technologies in the sub-6 GHz radio bands in an indoor realistic environment able to guarantee high-fidelity, scale, and repeatability of experiments. This is crucial for sub-6 GHz testing indoor deployments such as offices, malls, and airports that are characterized by fast-varying environment, spatially and time-varying interference, significant multi-path effect, and continuous mobility of surrounding objects.

To address this need, in this article we discuss for the first time Arena, an open-access wireless testing platform based on an indoor 64-antenna ceiling grid connected to programmable SDRs for sub-6 GHz 5G spectrum research. Arena is located in the open-space laboratory on the fourth floor of the Northeastern University Interdisciplinary Science & Engineering Complex. Its main contributions can be summarized as follows:

- **Real-time real-channel evaluation platform:** Arena is an open-access testing platform that can be used to run real-time experiments. It is accessible through the Internet and it can be used to prototype, develop, and experimentally evaluate new emerging technologies running real-time experiments leveraging the testbed SDRs and real indoor wireless channel characteristics.
- **Fully-synchronized testbed:** Arena employs a 24-SDR rack driving a total of 64 transmit/receive antennas deployed on a ceiling grid layout covering an overall area of $2240\,\text{ft}^2$. The radios are synchronized via clock distributors and connected to the antennas using identical equal-length cables, ensuring full symbol-level synchronization throughout the whole testbed. This enables applications such as massive MIMO, cooperative multi-point MIMO, and synchronized distributed systems.
- **Repeatable, flexible, and scalable indoor experiments:** Arena's 64 antenna grid provides a plethora of possible network topologies and the scale to foster new technology development. Its design ensures unchanged locations throughout the experiments and guarantees the integrity of the collected experimental data. A server rack of 12 identical machines drives the radios and guarantees the same computational power to each one of them toward a fair evaluation. Arena's clean three-tier design made of the server rack, the radio rack, and the ceiling grid addresses typical SDR deployment issues such as antenna orientation, cable non-linearities, and, ultimately, guarantees experiment repeatability.

The rest of this paper is organized as follows. In Section 2, we outline the testbed design and system architecture, while we describe the Arena hardware and software components in Section 3. In Section 4, we explain how to perform experiments on the testbed, while Arena's experimental capabilities are described in Section 5. Finally, related work is surveyed in Section 6, while Section 7 concludes our work.

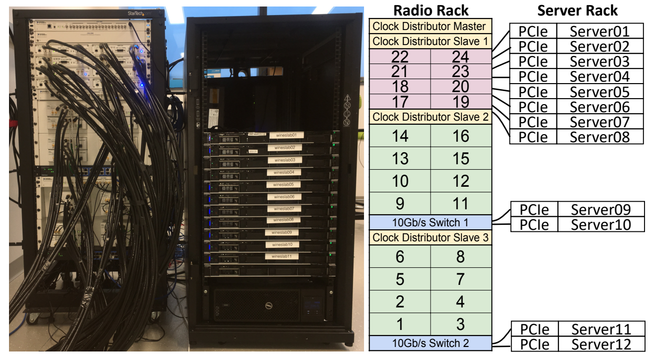

Figure 1: Radio and server rack physical and logical configuration.

2 TESTBED DESIGN AND SYSTEM ARCHITECTURE OVERVIEW

Arena provides researchers with a software control framework and radio hardware to evaluate wireless development on a multitude of different radio configurations, topologies, and channel conditions. Furthermore, it offers the capability of scaling up the testing environment by just changing a few lines of code, with the ultimate guarantee of reproducible experiments. Arena is based on a three-tiered architecture, the server rack, the radio rack, and the antenna grid.

The Server Rack. The server rack consists of 12 servers individually accessible through a top-of-the-rack gateway responsible for authenticating users. The platform is accessible from inside the Northeastern University intranet, as well as through the Internet via the College of Engineering (COE) Gateway, which keeps an up-to-date list of allowed users. Servers are in charge of driving the SDRs performing the transmit and receive baseband processing operations. They are identical to each other both on hardware capabilities, kernel version, operating system, and installed software, to guarantee uniform computational power and fair operations across the whole testbed. Moreover, servers employ the Network File System (NFS) protocol to mount user disk spaces and to maintain consistency of new software deployments and files across the whole rack. Servers connect to SDRs through a dedicated PCIExpress network card, offering two additional network interfaces at 10 Gbit/s each. They are also connected to the gateway through standard 1 Gbit/s interfaces. Each server connects to radios in one of two possible ways: *one-to-one* driving, and *one-to-four* driving, depending on the model of the radio to be driven.

One-to-one driving: Eight of the 12 servers are connected one-to-one to individual Universal Software Radio Peripheral (USRP) X310 SDRs via a dedicated 10 Gigabit network interface. The USRP X310 is a high-performance, scalable SDR platform whose hardware architecture combines two extended-bandwidth daughterboard slots covering DC–6GHz with up to 120 MHz of baseband bandwidth. The 10 Gigabit interface provides high bandwidth and a low-latency connection between servers and SDRs.

One-to-four driving: The remaining four servers are organized in pairs, each pair driving eight USRP N210 SDRs through a TRENDnet TEG-30284 10 Gigabit switch, for a total of 16 USRPs N210. The USRP N210 is a high-bandwidth, high-dynamic range radio designed to operate from DC to 6 GHz. The USRPs N210s are driven over 1 Gigabit Ethernet interfaces through the 10 Gigabit switches.

The Radio Rack. The radio rack is composed of 16 USRPs N210, eight USRPs X310, four clock distributors, and two 10 Gigabit switches, for a total of 24 synchronized SDRs. These house 32 daughterboards, each having one TX/RX and one RX2 antenna frontends. The radio and server rack layouts are shown in Figure 1. The SDRs in the rack are logically organized into 8-radio groups for a total of three groups. Each of them is provided with time and frequency synchronization by an OctoClock clock distributor (for a total of three clock distributors). These are in turn synchronized to a master clock distributor able to generate time and frequency signals. To connect the master clock distributor to the three slave clock distributors and the latter to the SDRs, we employed 54 identical and same-length cables. These cables guarantee clear reference signals and identical delays across all the 24 radios, which is essential for full synchronization across the whole rack.

With the goal of load balancing the network traffic between the two 10 Gigabit network interfaces of each server, the radio rack networking has been configured to partition the SDRs into sub-networks. Specifically, each USRP X310 is on its own private sub-network, while the USRPs N210 are grouped into four different 4-device sub-networks. Given the baseband processing capabilities of USRPs X310 (200 MSamples/s) and of USRPs N210 (25 MSamples/s), this configuration aims at load balancing the traffic over the two 10 Gigabit/s interfaces of the servers. This guarantees that the bandwidth of these interfaces suffices to drive up to four USRPs N210 or one USRP X310 through UHD (32bit/Sample).

The Antenna Grid. Each SDR houses one or two radio frequency daughterboards, each of which has two antenna frontends, namely TX/RX and RX2. Each input port connects to one antenna hanging off the ceiling through a 100 ft long cable. Each daughterboard connects to one *antenna pair* formed by one transmitting and one receiving antenna. Each USRP X310, thus, connects to four antennas, while each USRP N210 connects to two. A total of 64 identical 100 ft long cables are employed to connect 32 daughterboards housed in the radio rack to 32 *antenna pairs* hung off the ceiling. Same cable lengths ensure identical signal delays and guarantees symbol-level synchronization across the whole testbed, verifiable through an oscilloscope. The antenna grid floor plan layout is shown in Figure 2. The 64 antennas are deployed across 8 rails, each hosting four equidistant *antenna pairs* (8 antennas). With a spacing of 5 ft between *antenna pairs*, and 12 ft between rails, Arena covers an overall deployment area of 2240 ft^2. Being antennas hung off the ceiling, Arena offers unique Line of Sight (LOS) conditions with respect to similar size indoor testbeds, yet preserving the wireless channel characteristics typical of office-like environments. Its grid layout eases topology changes as well as long-distance communications without requiring physical relocation of the radios. Last, in spite of the multitude of radio testing topologies that the 64-antenna grid offers, additional topologies can easily be deployed on-demand thanks to the sliding rails that allow each antenna to be relocated for application-specific scenarios, as illustrated in Figure 2. The latest Arena configurations will be available on the WiNES Lab website.

3 HARDWARE AND SOFTWARE COMPONENTS

In this section, we provide a detailed description of Arena's design choices, as well as of its hardware and software configuration.

3.1 Access System Configuration

Arena is an open upon-grant platform, which any academic or industry researcher can access upon receiving a Northeastern University COE sponsored account. The use of Arena is regulated through the COE gateway through a Secure Shell (SSH) connection to a gateway. From the latter, it is possible to connect via SSH to the 12 machines in the Arena server rack, namely `wineslab01-12`. Once logged in, servers will automatically mount the account holder's network disk space through the NFS protocol. This allows users to access the files and programs installed on their network disk space from each of the 12 servers. Users have full permissions on contents located in their `home` directory, while permission to read, write, and execute other users' files is upon specific users grant, and denied by default. This guarantees users' privacy, files security, and keeps the single users' dependencies isolated.

3.2 Server Rack Configuration

The server rack is composed of 12 servers, a gateway, and a switch. The servers are Dell EMC PowerEdge R340 machines, namely `wineslab01-12`, running Ubuntu 16.04 LTS with

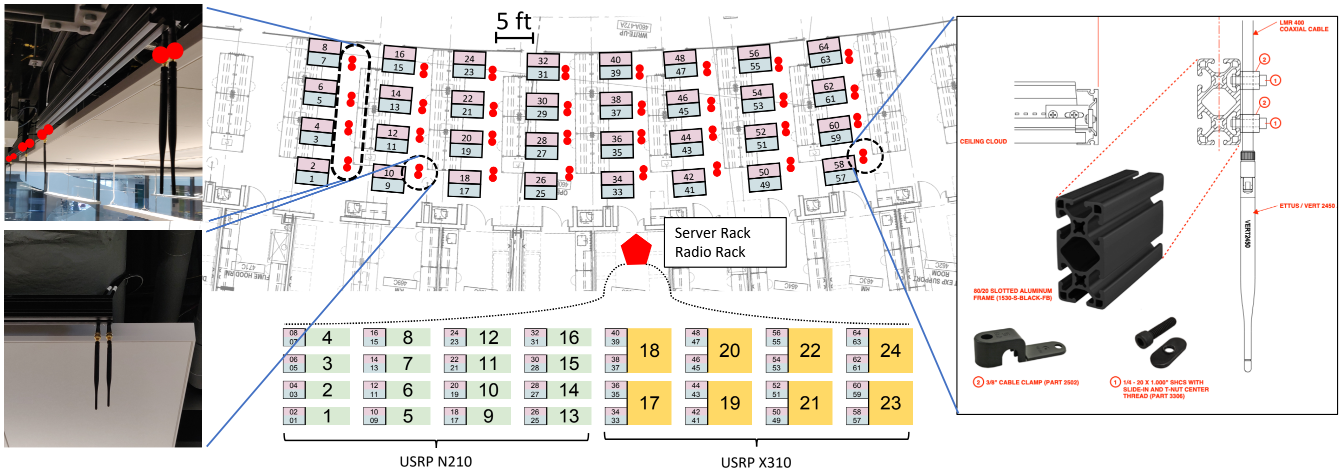

Figure 2: Arena antenna grid layout.

`4.15.0-50-generic` Linux kernel, and provide the computational power to drive the 24 SDRs. Specifically, each server has a 6-core (12-threads each) Intel Xeon E-2186G processor with 3.80 GHz base frequency (max 4.70 GHz) and four 8 GB DDR4-2666 RAM with 2666 MT/s speed.

Since high-speed connection and low-latency control are the keys to efficient software baseband processing, each server employs an additional Intel X520 Dual Port 10 Gigabit DA/SFP+ network card to communicate with the radios. This additional network card adds two network interfaces leveraging the SFP+ technology to establish a fast and reliable link to the radios and an aggregate data-rate of 20 Gbit/s.

A set of open-source software tools has been pre-installed on the servers to communicate with the SDRs and drive them. Among these, there are GNU Radio 3.7.13, srsLTE, UHD 3.14, Python 2.7, and Python 3.5, which are ready to be used by any user to run wireless experiments. A standard Gigabit Ethernet interface connects each server to the WiNES Lab gateway through a 24-Port Netgear GS324 Gigabit Ethernet switch. The gateway is implemented on a Dell Precision 5820 machine running Ubuntu 16.04 LTS with `4.15.0-50-generic` Linux kernel and implements server access control and network security features, as well as it provides Internet access to each of the 12 servers.

Powering the server rack might require a high power supply, which potentially varies over time. To this end, the power supply system is based on two APC Metered Rack Power Distribution Units (PDU) AP7811B and a Dell 5000 VA 208 V Smart Uninterruptible Power Supply (UPS). This protects all the server rack devices from power spikes and surges and provides approximately one hour of emergency power in case of outages. Moreover, the UPS is powered through an emergency power receptacle, active even in case of a power outage in the building, as a second level of power outage protection.

3.3 Radio Rack Configuration

The radio rack houses 16 National Instruments (NI) USRP N210, eight NI USRP X310, four NI OctoClock clock distributors, and two 10 Gigabit switches. USRPs are experimental hardware radio platforms completely controllable through software programs. They embed a Field-programmable Gate Array (FPGA), Analog-to-Digital Converters (ADCs), and Digital-to-Analog Converters (DACs) and are particularly suitable to design, test, prototype, and deploy wireless radio communication systems and protocols.

The USRP N210 is a networked device with high-bandwidth and dynamic range processing. It embeds a daughterboard slot allowing for bi-directional wireless communication and is controllable via software through its Gigabit Ethernet interface. Specifically, it includes a 100 MS/s Xilinx Spartan 3A-DSP 3400 FPGA, a 14-bit 100 MS/s dual ADC, a 16-bit 400 MS/s dual DAC. The host sampling rate is up to 50 MS/s, while its internal clock rate equals to 100 MHz. Furthermore, its modular design allows to combine and synchronize multiple USRPs N210 for more advanced MIMO applications via a MIMO cable or external synchronization.

The USRP X310, instead, is a high-performance scalable device embedding two daughterboard slots as well as a user-programmable FPGA. The two daughterboard slots, allowing for two bi-directional transmit-receive chains, make it particularly suitable for MIMO applications. This device can be controlled via software through two 200 MS/s aggregate SFP+ slots. Specifically, the USRP X310 includes a 200 MS/s XC7K410T Kintex-7 FPGA, a 14-bit 200 MS/s dual ADC, a 16-bit 800 MS/s dual DAC. The host sampling rate is up to

200 MS/s, while its internal clock rate is 200 MHz. As for the USRP N210, multiple X310 can be synchronized through external synchronization for MIMO applications. Both USRPs N210 and X310 are able to operate from DC to 6 GHz.

Finally, USRPs N210 and X310 are fit with one and two CBX daughterboards for communication purposes, respectively. A CBX daughterboard is a full-duplex, double-chain wideband transceiver allowing USRPs to operate in the 1.2-6 GHz frequency range with up to 120 MHz instantaneous bandwidth and up to 22 dBm transmit power. The CBX can serve a wide variety of application areas, including WiFi research, cellular base stations, cognitive radio research, and radar [18].

3.4 Grid Configuration

One of the highlight design choices of Arena is the 64-antenna ceiling grid concerning an 8×8 array that covers an overall area of 2240 ft^2, where each antenna point is cabled to the radio rack. Arena is based on 64 American Wire Gauge (AWG) RG8-CMP [7] low-attenuation, fireproof 100 ft long SMA-to-SMA connection cables that have been specifically designed for indoor applications. Using 64 same-length cables guarantees equal delays in symbol transmission and reception across the whole testbed, despite the antenna location. Guaranteeing same delays all the way to the antennas is crucial for transmission schemes such as MIMO, where different antenna connector length might compromise the transmission synchronization. The cable length has been selected as the shortest one connecting the farthest antenna point to the rack to reduce signal power loss, which equals to 6.8 dB and 11 dB over 100 ft length at 2.4 GHz and 5.0 GHz, respectively, which can be however compensated with transmission and reception gains. Guaranteeing consistent delays across the whole testbed comes at the price of having tens of extra feet of cables to bundle. These have been professionally coiled across the ceiling avoiding loops that might result in undesirable electromagnetic effects.

For over-the-air communications, Arena features 3 dBi gain omnidirectional dualband VERT2450 antennas for transmission and reception (see Figure 2). These toroidal-radiation dipole antennas are optimized to work in the 2.4-2.5 GHz and 4.9-5.9 GHz operating frequency bands and offer a 50 Ω nominal impedance [3].

The 64 antennas are mounted on eight 15 ft rails hung off the ceiling. Rails have a 1.5×3 inches rectangular T-slotted profile with six open slots on each of its sides and one on the front side. Each rail hosts four *antenna pairs* spaced 5 ft from each other, while same pair antennas are spaced 1 inch only to mimic a transceiver radio device. The rail's robust structure provides enough strength to support the weight of eight AWG cables each, while their modular design permits antennas relocation along their whole length. In fact, antenna locations can be effortlessly adjusted by just sliding them along rails as shown in Figure 2.

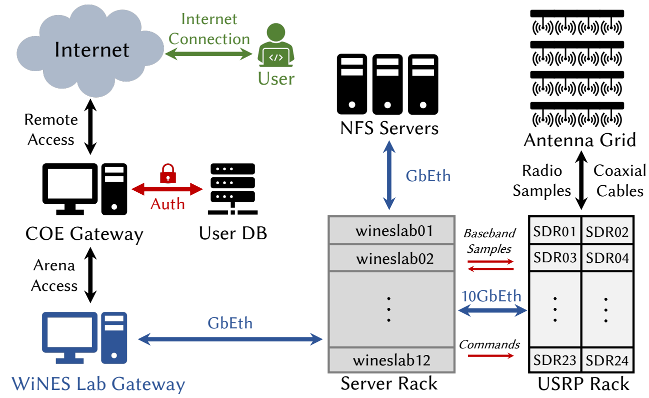

Figure 3: Arena access system diagram.

4 LIFE-CYCLE OF AN EXPERIMENT

To access Arena and perform real-time experiments, external users can request a Northeastern University College of Engineering (COE) sponsored account to the WiNES Lab mailing list owner[1]. Upon getting a sponsored account, users can authenticate to the WiNES Lab Gateway[2] through the COE Gateway[3] which is accessible from the Internet. At their first access, users will be allocated dedicated network disk space, accessible through any machine under the COE domain via the Network File System (NFS) protocol. Once logged into the WiNES Lab Gateway, it is possible to SSH to any of the 12 Arena servers[4].

Since each server `wineslab01-12` drives only a subset of the available radios, the server selection can be made upon the user's experiment of choice. In this way, users can access one, some, or all of the 12 servers depending on their needs. Specifically, accessing servers `wineslab01-08` will allow driving one and only one USRP X310 per server (SDR 17 - SDR 24), servers `wineslab09-10` can be accessed to drive up to 8 USRPs N210 (SDR 9 - SDR 16), while servers `wineslab11-12` can be accessed to drive the remaining 8 USRPs N210 (SDR 1 - SDR 8). Finally, the gateway keeps track of logged users to avoid server overloading and possible conflicts of users driving the same radios.

Despite users being able to install their own software of choice on the network disk space allocated to them, basic development and testing software, such as Python, GNU Radio, and srsLTE, has already been installed on the servers and

[1]`wineslab-owner@coe.neu.edu`
[2]`wineslabgate.coe.neu.edu`
[3]`gateway.coe.neu.edu`
[4]wineslab01-12.coe.neu.edu

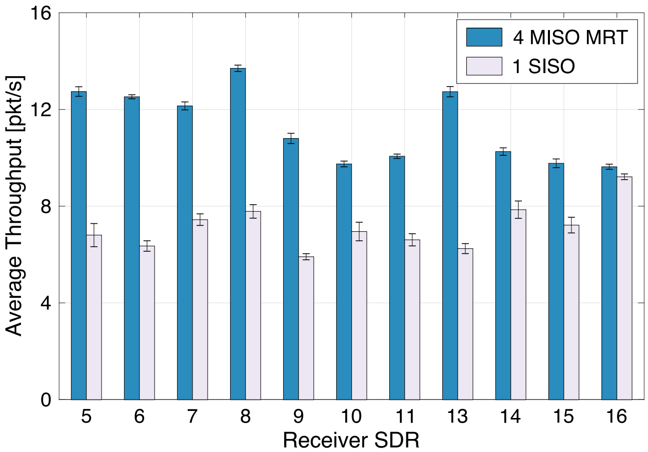

Figure 4: Average 4-MISO and SISO comparison at 11 different receivers. 95% confidence intervals are shown.

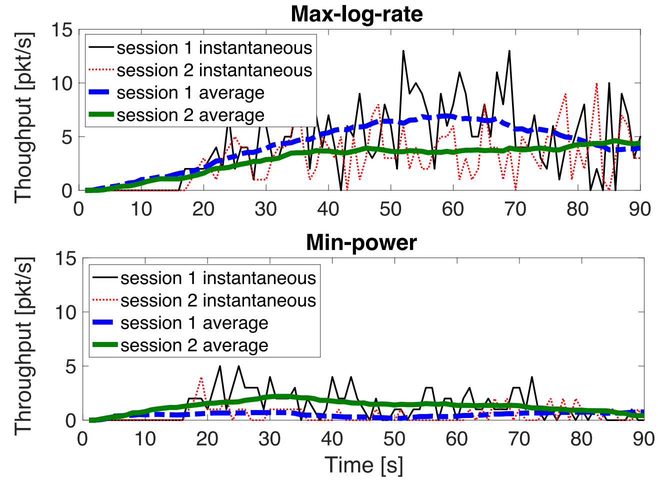

Figure 5: Single run and average results for two different control problems on a 14-node ad hoc network, using WNOS.

it is accessible by all users. On Arena, performing real-time wireless experiments is as simple as running pre-compiled software such as GNU Radio transmit an receive programs (e.g., `benchmark_tx.py` and `benchmark_rx.py`), or srsLTE core network and base station programs (e.g., `srsepc` and `srsenb`) and specify the desired radio to be driven by command line tool (e.g., `--args="addr=192.168.10.2"` to drive SDR 1) for USRP N210, while explicit radio addressing is not needed for USRP X310, which are one-to-one driven by servers `wineslab01-08`. The USRP Hardware Driver (UHD), a user-space library that runs on a General Purpose Processor (GPP), handles the baseband samples between the SDR and the control host. The control host software (e.g., GNU Radio), will report network status and measured metrics to the user such as transmitted, received, and correctly decoded packets, overall network throughput, and nodes interference levels, which can be saved on network disk or external drive for further analysis. To terminate an experiment session, the user can simply log out from the servers in use and from the WiNES Lab gateway.

Ultimately, Arena's real-time testing capabilities can be employed to experiment with simple point-to-point links, test multi-hop transmissions, evaluate cellular network performance, or implement MIMO communication schemes, both for real-time research validation and live demonstrations. We provide an overview of Arena experimental capabilities in the next section.

5 EXPERIMENTAL CAPABILITIES

While Arena can be leveraged to test point-to-point transmission techniques, such as narrowband and OFDM, employing diverse modulations, transmission powers, and other physical layer parameters, in this section we focus on providing some experimental use case scenarios where we test more complex communication schemes as well as evaluate some published work on Arena.

MIMO Capabilities: Among Arena highlights is its full-testbed symbol-level synchronization. This can be employed to implement distributed MIMO transmission schemes with the goal, for instance, of increasing the SINR of a wireless communication link. We implemented a 4-MISO transmitter employing Maximum Ratio Transmission (MRT) beamforming at SDRs 1-2-3-4, and evaluated its performance against single antenna (SISO) transmission toward several single antenna receivers [13, 14] for the same overall output power. Figure 4 compares the received throughput for the two transmission schemes at 11 different receiver locations across the testbed. During this set of experiments, changing the network topology was as easy as addressing different receiver devices from GNU Radio, and did not require any SDR/antenna relocation.

Ad Hoc Networks: We also demonstrated ad hoc wireless networks implementing an instance of WNOS [11]. WNOS is a wireless network operating system for ad hoc networks that provides automated network control, interfacing the network designer with a simple control interface. WNOS takes network control programs defined on a centralized abstraction of the network, and automatically generates distributed cross-layer control programs based on distributed optimization theory. These are, then, executed by each individual network node on an abstract representation of the radio hardware. We implement a 14-nodes WNOS prototype

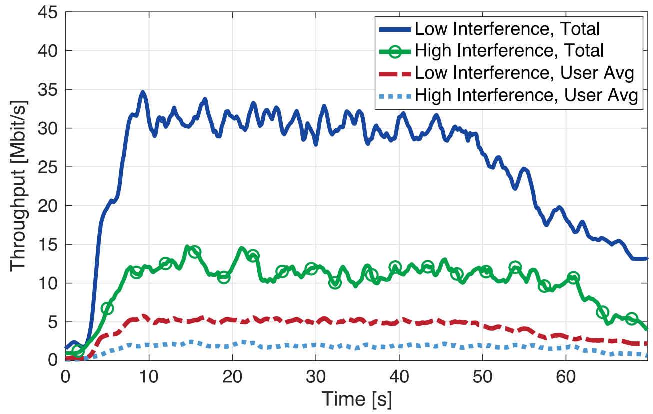

Figure 6: Network throughput in high and low inter-cell interference scenarios using 2 eNBs and 6 UEs with srsLTE.

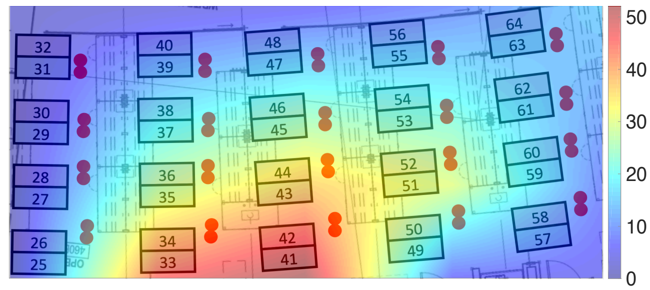

Figure 7: Heatmap of sensed Wi-Fi packets per second at different locations of Arena.

on Arena, where two source nodes intend to deliver data to two destinations through 12 relay nodes, in a wireless multi-hop fashion. As source, relay, and destination nodes, we use SDRs 3-11, SDRs 1-2-5-6-7-9-10-13-14-15, and SDRs 8-16, respectively. We employ WNOS to dictate two different network behaviors, namely *max-rate* and *min-power* (see [11] for details). The network performance for the two traffic sessions under the two different control problems is shown in Figure 5.

Cellular Networks: Arena can be used to easily evaluate cellular network scenarios with a high degree of realism. We herein showcase the implementation of a multi-cell LTE network and evaluate its performance for two different scenarios: high inter-cell interference and low inter-cell interference. In the former, two eNBs are located in close proximity to one another and have almost completely overlapping coverage areas, while in the latter, the two eNBs are located further away from each other. For both scenarios, each eNB serves three mobile subscribers continuously requesting data at the maximum rate. We used srsLTE to implement the cellular network, a pre-installed open-source software offering a standard-compliant implementation of the LTE protocol stack for base station (eNB), User Equipment (UE), and Evolved Packet Core (EPC) [10, 19]. We implemented the eNBs on USRPs X310, specifically, we employed SDRs 21 and 22 for the high interference scenario, and SDRs 17 and 24 for the low interference one. As UE, we used Samsung Galaxy S5 commercial cellular phones. Figure 6 shows the total network throughput, as well as the average per-user throughput for the two deployments. Results report how inter-cell interference negatively affects the user average throughput and the sum network performance.

Cognitive Radio Networks: Arena can also be used to implement spectrum-sensing-based network solutions such as cognitive radios. Concepts like spectrum sharing, opportunistic spectrum access, and spectrum management typically rely on information gathering by idle listening on the wireless channel [1, 15, 28]. We herein show how Arena can be leveraged to gather information about Wi-Fi activity in the surrounding environment. Specifically, we leveraged an IEEE 802.11 GNU Radio implementation [2] to implement an SDR-based Wi-Fi receiver at SDRs 13-14-15-16-17-18-19-20-21-22-23-24 and sense the Wi-Fi activity on Wi-Fi channel 6. Figure 7 illustrates the heatmap of the sensed Wi-Fi activity across the employed devices.

6 RELATED WORK

Over the last decade, open-access experimental SDR-based testbeds have been of paramount importance in testing protocols and technologies both for academic research purposes and for industrial applications. Universities, companies, and consortia have worked on designing a multitude of different experimental testing platforms varying per scale, computational power, deployment environment, and channel characteristics [4–6, 8, 9, 16, 17, 21–27].

Early efforts such as UFMG [23], UFRGS [25], LESC [27], and Iris [21] laid the foundation for larger scale deployments and future design choices. Among others, experimental platforms such as CorteXlab [6] and NITOS Future Internet Facility [16], provided researchers with the tools for indoor Wi-Fi and LTE experimental evaluation, while UNIVBRIS [26] allows outdoor small-city scale testing for the IoT paradigm. Regarding indoor design efforts, we highlight CORENET [12, 20], an under-development testbed envisioning 48 nodes deployed across the hallways of a four-story building on campus; and ORBIT [17], a mixed deployment of software-defined radios and commercial devices ideal for non-line-of-sight experiments and wall penetration testing. Among the other SDR-based testing platforms it is worth mentioning Colosseum [4], and the Drexel Grid [5]. The former is a gargantuan channel emulator tailored to the DARPA Spectrum Collaboration Challenge that allows researchers to test devised approaches on channels emulated through 128 two-channels SDRs. The latter, instead, is a ceiling testbed with a number of USRPs coexisting with simulated nodes. Both these platforms are able to use a dataset of recorded real channels characteristics to emulate over-the-air radio communications. Among the large-city-scale outdoor deployments, two leading efforts are the Platform for Open Wireless Data-driven Experimental Research (POWDER) [9] and the Cloud Enhanced Open Software Defined Mobile Wireless Testbed for City-Scale Deployment (COSMOS) [8]. These work-in-progress wireless platforms are based on dozens of nodes supporting different transmission technologies such as cellular networks and Wi-Fi, which allow researchers to evaluate their systems in outdoor city-scale configurations. In conclusion, Arena differs from related work for its unique full testbed symbol-level synchronization, large-scale line-of-sight indoor deployment, and real-time experimental capabilities over real wireless channels.

7 CONCLUSIONS

We presented Arena, an open-access wireless testing platform for sub-6 GHz 5G spectrum research. Arena is a unique indoor testing platform in an office space environment. It is based on 12 computational servers, 24 software defined radios, and a total of 64 antennas organized in an 8×8 grid hanging off the ceiling and covering an overall area of 2240 ft^2. We showed how Arena can be employed to implement and evaluate complex wireless technologies such as MIMO transmission schemes, ad hoc networks, multi-cell LTE networks, and cognitive radios. We hope that its open-access system, its three-tiered architecture, its full symbol level synchronization, and its unique line of sight indoor ceiling-grid layout ensuring reconfigurable, scalable, and repeatable real-time real wireless channel experiments will foster the development of new 5G/6G technologies, Internet of Things (IoT), cognitive radio/dynamic spectrum access, and massive MIMO applications.

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