Ad Hoc Networks 111 (2021) 102305

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

A city-wide experimental testbed for the next generation wireless networks☆

Zhongyuan Zhao [a,*], Mehmet C. Vuran [a], Baofeng Zhou [a], Mohammad M.R. Lunar [a], Zahra Aref [a], David P. Young [b], Warren Humphrey [c], Steve Goddard [d], Garhan Attebury [e], Blake France [f]

[a] Department of Computer Science and Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588, USA
[b] Federal Communications Commission, City of Lincoln, Lincoln, NE, USA
[c] Olsson, Lincoln, NE 68508, USA
[d] College of Liberal Arts and Sciences, University of Iowa, Iowa City, IA 52242, USA
[e] Holland Computing Center, University of Nebraska-Lincoln, Lincoln, NE 68588, USA
[f] Information Technology Services, University of Nebraska-Lincoln, Lincoln, NE 68588, USA

ARTICLE INFO

Keywords:
Dynamic spectrum access
Internet of Advanced Things
Spectrum sensing
Radio Frequency Machine Learning
Underground radio
USRP

ABSTRACT

To facilitate research in dynamic spectrum access, 5G, vehicular networks, underground wireless communications, and radio frequency machine learning, a city-wide experimental testbed is developed to provide realistic radio environment, standardized experimental configurations, reusable datasets, and advanced computational resources. The testbed contains 5 cognitive radio sites, and covers 1.1 square miles across two campuses of the University of Nebraska-Lincoln and a public street in the city of Lincoln, Nebraska. Each site is equipped with a 4x4 MIMO software-defined radio transceiver with 20Gbps fronthaul connectivity. Additional cognitive radio transceivers with an underground 2x2 MIMO antenna are included in a site. High speed fronthaul network based on dedicated fiber connects the 5 sites to a cloud-based central unit for data processing and storage. The testbed provides researchers rich computational resources such as arrays of CPUs and GPUs at the cloud and FPGAs at both the edge and fronthaul network. Developed via the collaboration of the university, city, and industrial partners, this testbed will facilitate education and researches in academic and industrial communities.

1. Introduction

Next generation wireless networks will be characterized by larger volume, faster information transfer, and diversity. Wireless industry has been altering conventional license-based spectrum access policies through approaches utilizing unlicensed spectrum. This leads to dynamic spectrum access (DSA), where unlicensed use of a spectrum should avoid harm to licensed users, or should ensure a fair share of spectrum with other unlicensed users. DSA places an additional burden on business operations because revenue needs to be generated over dynamically changing resources, while providing expected quality of service to potential users. To address the challenges of spectrum, pricing, and privacy in the next-generation DSA solutions, it is necessary to utilize testbed capable of emulating realistic networks to model the complex behaviors of radio networks and environments.

Meanwhile, as today's Internet of Things applications bring new requirements to the evolving wireless standards, tomorrow's advanced use cases will derive these innovations through Internet of Advanced Things. Heterogeneous wireless technologies in public safety, infrastructure, smart agriculture, and rural broadband connectivity require a seamless wireless continuum across underground and over-the-air and urban and rural settings to bridge the digital divide. As a result, a variety of environmental configurations and experimental tools are required, which would be burdensome and sometimes prohibitive for many researchers to build. Open testbeds [1–7] would facilitate innovations by providing researchers experimental platforms.

Moreover, the emergence of data-driven wireless technologies, such as Radio Frequency Machine Learning (RFML), are shifting the ways of work towards ones that emphasize realistic radio environments, standardized and/or open datasets for repeatability, and intense computations. RFML is envisioned to replicate the success of deep learning in computer vision in which rapid advancements are achieved from repeatable and comparable experiments based on open datasets. To facilitate researches in RFML, testbeds need to have realistic radio envi-

☆ A preliminary version of this paper has appeared on Balkancom'19 (Zhao et al., 2019) [1].

* Corresponding author.
E-mail addresses: zhzhao@cse.unl.edu, zhongyuan.zhao@rice.edu (Z. Zhao), mcv@unl.edu (M.C. Vuran), bzhou@cse.unl.edu (B. Zhou), mlunar@cse.unl.edu (M.M.R. Lunar), zaref@cse.unl.edu (Z. Aref), DYoung@lincoln.ne.gov (D.P. Young), whumphrey@olsson.com (W. Humphrey), steve-goddard@uiowa.edu (S. Goddard), garhan.attebury@unl.edu (G. Attebury), blake.france@nebraska.edu (B. France).

https://doi.org/10.1016/j.adhoc.2020.102305
Received 17 January 2020; Received in revised form 27 July 2020; Accepted 14 September 2020
Available online 21 September 2020
1570-8705/Published by Elsevier B.V.

ronments, standardized experimental configurations, reusable datasets, as well as advanced computational resources.

To address aforementioned requirements, a city-wide testbed, Cognitive Secure Cloud-Radio Access Network (CoSeC-RAN), is developed through the collaboration with the City of Lincoln. CoSeC-RAN covers 1.1 square miles across two campuses of University of Nebraska-Lincoln and a public street in the city of Lincoln. It contains 5 high-end software-defined distribution units (SD-DUs) at the edge of Cloud-Radio Access Networks (C-RAN). Each SD-DU is equipped a sub-6 GHz Software-Defined Radio (SDR) transceiver and a 4 × 4 MIMO antenna array and connected to cloud-based central unit via 20Gbps fronthaul network. Additionally, two SD-DUs are equipped with underground (UG) MIMO antennas for researches of underground wireless sensors. The CoSeC-RAN has rich computational resources. High performance computing clusters with arrays of Central Processing Units (CPUs) and Graphics processing units (GPUs) are provided by the cloud at Holland Computing Center (HCC) [8], Field-Programmable Gate Arrays (FPGAs) are available at the SD-DUs (edge) and fronthaul network. Projects at various scales and stages could be supported by a variety of general cloud computing resources, such as dedicated virtual machine and computing clusters.

2. Related work

Notable early initiatives of cognitive radio testbeds include ORBIT testbed [2] from Rutgers University, WARP platform [9] from Rice University, and CORNET [3] and LTE-CORNET [4] from Virginia Tech. The ORBIT consists of an indoor radio grid with 400 nodes supplemented by a number of outdoor and vehicular nodes deployed on or around the Rutgers campus for end-user evaluations in real-world settings. The nodes include WiFi, Zigbee, WiMAX and SDR radios USRP [10]. WARP provides a collection of hardware, software, and reference designs for users to build their own testbeds. The CORNET [3,4] is a campus-wide open testbed with over 48 SDR transceivers and a number of experimental spectrum licenses. According to [11], typical SDR hardwares are USRP [10], WARP [9], and popular software are GNURadio [12], LabView, and Matlab, where the combination of USRP and GNURadio is most popular.

FIT [5] is an initiative of large-scale open testbed in France. FIT has three components: FIT-Wireless is for indoor WiFi, 5G, and cognitive radio includes 4 open testbeds from 4 sites, each with tens of WiFi and SDR nodes. FIT IoT-LAB is for IoT research, with testbeds located at 6 sites for a total of 2728 nodes. FIT Cloud has three platforms and is for cloud design, which provides synergy with FIT-Wireless and FIT-IoT.

Platforms for Advanced Wireless Research (PAWR) [13] is another initiative of large-scale open testbeds supported by National Science Foundation in the U.S.. Currently, three testbeds are granted: POWDER-RENEW [6], led by University of Utah and Rice University, covers a total of 3.3 square miles in University of Utah campus and downtown Salt Lake City, and offers data-driven researches for dynamic spectrum sharing and massive MIMO capabilities. Another testbed, COSMOS, led by Rutgers University, Columbia University, and New York University, covers 1 square mile in a densely-populated neighborhood in West Harlem, New York City. COSMOS is for millimeter-wave (mmWave) radio communications and dynamic optical switching technologies [7]. The third one, AERPAW [14], is led by North Carolina State University in partnership with Wireless Research Center of North Carolina, Mississippi State University, RENCI, Town of Cary, City of Raleigh, North Carolina Department of Transportation, Purdue University, University of South Carolina, and many other academic, industry and municipal partners. AERPAW aims to enable new advanced wireless features for Unmanned Aircraft Systems (UAS) and accelerate the integration of UAS into the national air-space.

The CoSeC-RAN testbed [1] shares the open access policy and some SDR hardware and software with ORBIT [2] and CORNET [3], but is focused on outdoor real-world settings. Moreover, the CoSeC-RAN testbed also adopts an architecture of Cloud-Radio Access Network (C-RAN), with Software Defined Radio (SDR) transceivers, and a cloud with CPU, FPGA, and GPUs available at both edges and the core, which is similar to the first two PAWR projects [6,7]. CoSeC-RAN testbed targets sub-6 GHz frequencies, and is currently focused on sub-1 GHz. Additionally, this testbed supports underground wireless researches in UHF band, and can be extended to mmWave radio communications.

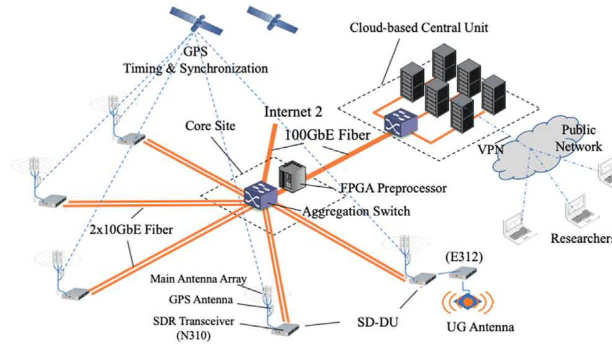


Fig. 1. CoSeC-RAN testbed architecture.

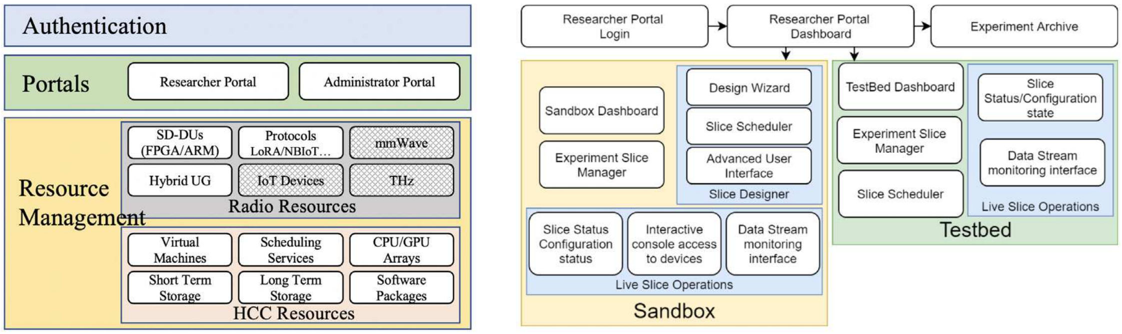
3. Testbed architecture

3.1. Hardware architecture

The architecture of CoSeC-RAN testbed, as illustrated in Fig. 1, is composed of Software-Defined Distribution Units (SD-DU), fiber Ethernet-based fronthaul network, and cloud-based central unit. The SD-DU, also called Cognitive Remote Radio Heads (CRRHs), contains a high-end 4 × 4 MIMO Software Defined Radio (SDR) transceiver that can be tuned to any sub-6 GHz frequency. Currently, there are 5 SD-DUs on 4 campus sites and 1 street site. All the SD-DUs are connected to the cloud-based central unit at HCC [8] via fiber Ethernet-based fronthaul network. HCC is a high-performance computing cloud where data processing and storage take place. GPS-based clock distribution provides the SD-DUs capability of coherent sampling.

This architecture allows wireless experiments at multiple levels. With the 4 × 4 MIMO SDR transceiver at each SD-DU, researchers could conduct a host of experiments, such as point-to-point MIMO communication, mesh network, and single site with base-station and mobile devices in realistic environments. With multiple synchronized SD-DUs and cloud-based central unit, the testbed further support network experiments, such as coordinated multipoint (CoMP), Cooperative MIMO (CO-MIMO) and distributed spectrum sensing. With the flexibility of the SDR transceivers and high-speed fronthaul network, the testbed could also be configured with existing protocols and standards to interface with off-the-shelf wireless devices so that application-level experiments could also be conducted.

The 5 sites of SD-DUs are selected strategically to support experiments of heterogeneous wireless technologies. These five sites covers 2 campuses of the University of Nebraska-Lincoln and a public street of the city of Lincoln. The 3 sites on the *city campus* provides typical urban environments with buildings and streets as well as other co-located wireless networks. The site located on the public street could support wireless experiments for vehicular to infrastructure (V2I) with speed limit of $65km/h$. Moreover, the site on public street also includes an extra SDR transceiver connected to an underground(UG) MIMO antenna, which could support UG-to-AG wireless experiments. The site on *Nebraska Innovation Campus* is on the rooftop of a building in an open environment. Furthermore, a manhole next to the building is also included to provide wireless experiments of wastewater sensors. In the



(a) Software System Architecture (b) Research User Workflow

Fig. 2. CoSeC-RAN testbed software and workflow. The shaded blocks in (a) are components to be added in the near future.

future, mmWave and Terahertz communication devices will also be included.

The fiber Ethernet-based fronthaul network provides 2 lines of 10Gbps connectivity for each SD-DU to the central unit. An FPGA card with 400Gbps throughput at the core site could not only support experiments for the fronthaul network itself but also allows interfacing with commercial base-stations based on eCPRI protocol.

The cloud-based central unit hosted by HCC provides researchers rich computational resources, including array of CPUs and GPUs as well as data storage space. HCC already supported several RFML projects with offline training [15,16]. In this testbed, SD-DUs are directly connected to and controlled by CPUs and GPUs, which allows online experiments of Radio Frequency Machine Learning. Frames of IQ data from/to the SDR transceiver could also be saved in the distributed file systems of HCC for further analysis and replication.

3.2. Software architecture

CoSeC-RAN's software components will be developed incrementally by software engineers with a layered architecture as illustrated in Fig. 2(a). The components of radio resources will be developed from scratch, while the rest through reusing or customizing existing components in HCC platform. The resulting system is a composition of stateless/state-aware systems that enable scalability, testability, and a high degree of service re-use.

The first layer of CoSeC-RAN will contain the Authentication system. The second layer will include the user facing front end. The third layer will include resource management serving as the gatekeeper to all the resources of HCC and the matrix of radios as described in Section 3.1. The user facing front end will be a cloud hosted web portal that orchestrates the various aspects of CoSeC-RAN. The mission of the Researcher Portal is to abstract away the underlying infrastructure (radios, virtual machines, resource scheduling) in such a way that a user can very quickly log in, configure an experiment, and run the experiment. Users will generally only need to know the goals and objectives of their experiments to use CoSeC-RAN. The Administrator Portal will allow for administration of CoSeC-RAN. At the resource management layer, the most notable HCC resources are shown in Fig. 2(a). Virtual machines will be available to be configured as servers or workstations. High performance short term storage will be available for use during live tests. Long term archival storage will be available for maintaining libraries of past experiment Profiles as well as their results. The Scheduling Service will provide the proper allocation of slices for all resources across all levels. The CPU and GPU arrays are available to provide either real-time or post experiment analysis. Radios will include at minimum the resources specified in Fig. 2(a), each of which is required to support the wireless exemplary use cases of CoSeC-RAN.

This administration system provides researchers tutorials and procedures to reserve radio and computational resources of the testbed according to their individual needs. Once scheduled, the system will configures the testbed and run the experiments at scheduled time slots.

3.3. Research user workflow

Users will primarily perform four key activities: staging tests, scheduling tests to be executed, monitoring in-progress tests, and retrieving/viewing test results. CoSeC-RAN brings a unique and interactive on-site experimentation capability (the staging phase), which is similar to the early phases of a simulation development, where short scripts are tested to understand and evaluate the simulation platform before a full-blown simulation is run. Translating this to experimentation, during staging, the sandbox environment will support real-time workflow development by allowing users to interact in real-time with the radios and other equipment in the Experiment Slice (Fig. 2(b)). Logged in users will see a dashboard outlining their experiments that are awaiting execution, live, or completed. In the Sandbox, a user will scan through experiments that are available for editing and see high level statistics about them.

A user can manage an experiment through Slice Designer or Live Slice Operations if a slice has already been brought online. Slice Designer helps allocate and set up experiment resources, upon which the Design Wizard optimizes configuration of experiments related to specific exemplary use case applications called CoSeC-RAN Profiles. CoSeC-RAN Profiles will cover typical use cases. Profiles will include definitions for the network topology, disk/radio images, research/analysis software, and data files. The definitions can be stored collectively as a file, or a researcher can upload individual devices and FPGA image files. The wizard will continue to evolve through CoSeC-RAN's lifetime and Profiles will be enhanced and added. The Advanced User Interface will allow a user to tweak any individual component of the experiment that was automatically generated as part of a wizard built slice. An advanced user could build the entire slice from scratch, defining each component and feature. Once the experiment workflow is fully defined, it can be scheduled for deployment at scale and the slice will be locked in the Sandbox. An experiment with its designed resource slice will be promoted into the live testbed.

Previous experiments on CoSeC-RAN testbed can be reproduced either online or offline. For online reproduction, users first reserve the same resources through administration portal, then replay the previous experiments on the testbed based on their profiles and input data files. For offline reproduction of experiment, users only reproduce the computational process based on the published data files (e.g. raw IQ data) and research/analysis software. New ideas can be quickly tested and compared to the old ones. For RFML, open radio datasets from the testbed can simplify the development similar to open image datasets for computer vision. To preserve the large amount of raw radio data, HCC promises up to five years of backed up storage for regular archival data, and large datasets (e.g. several Petabytes) will be kept best effort but not backed up. Users can choose standardized or customized data storage plans accordingly.

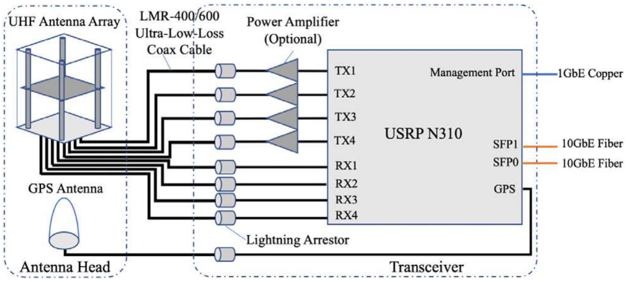
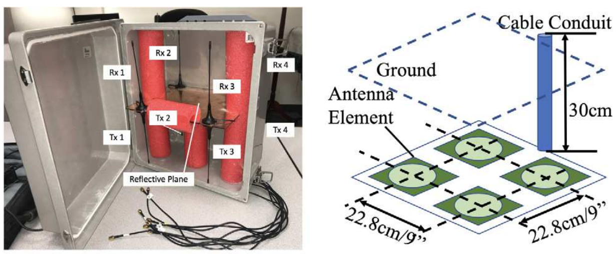


Fig. 3. Software defined distribution unit schematic.



(a) UHF Antenna Array (b) Underground Antenna Array

Fig. 4. UHF Antenna array: 2 × 2 uniform rectangular array.

4. Testbed implementation

In this section, detailed implementation of the testbed are introduced to provide a clear picture of the technical capabilities of the testbed on different layers of wireless networks.

4.1. Software defined distribution unit

The SD-DU is a SDR transceiver that converts digital baseband IQ data from/to radio frequency electromagnetic waves. The schematic of the SD-DU is illustrated in Fig. 3. The core of SD-DU is a high-end Software Defined Radio (SDR) transceiver, Universal Software Radio Peripheral (USRP) N310 [17]. The N310 has 8 RF ports: 4 transmit (Tx) and 4 receive (Rx) channels. Each channel provides up to 100 MHz of instantaneous bandwidth, and covers a frequency range from 10 MHz to 6 GHz. The maximum output power of Tx port is 12–18 dBm [17].

The 8 RF ports of the SDR transceiver are connected to an UHF antenna array with 8 elements (4 Tx and 4 Rx) via ultra low loss coaxial cables. Without reusing Tx and Rx antenna, the extra loss and leakage of a RF circulator are eliminated. LMR-400/600 grade coaxial cable is selected, of which the insertion loss is 1.2/0.6 dB at 600 MHz and 3.2/1.6 dB at 2.4 GHz for a length of 50 ft. For each site, the 8 coaxial cables are made with the same length. At different sites, the cable length varies from 25 to 50 ft. A 3.3 V active GPS antenna [18] is connected to the SDR transceiver for clock synchronization. Since the UHF antenna array and GPS antenna are placed outdoor, lightning arrestors are added before the RF and GPS ports to protect the transceiver. Broadband RF amplifiers could be further added between the lightning arrestor and RF port to increase the Tx power.

It is impossible for a simple antenna array to cover the entire sub-6 GHz. Therefore, an UHF antenna array for sub-1 GHz band is designed, as shown in Fig. 4(a). The antenna element is an off-the-shelf omnidirectional monopole antenna with a gain of 6 dBi, which is originally used in USB TV dongles. The UHF antenna array, as shown in Fig. 4(a), contains two 2 × 2 uniform rectangular arrays mounted on both sides of a reflective plane, and placed in a weatherproof enclosure. The distance between 2 nearest antenna elements is 175 mm, which is $\lambda/4$ of 428 MHz radio wave, $\lambda/2$ of 856 MHz, where λ denotes the wavelength of electromagnetic wave in the atmosphere. Thus, this UHF antenna array is capable of beamforming from 428 to 856 MHz without grating lobes.

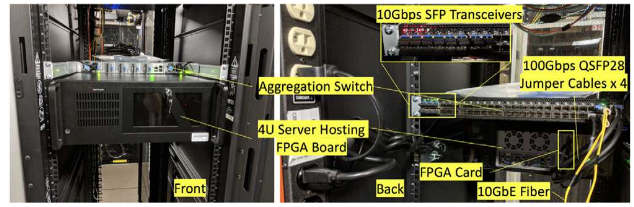


Fig. 5. Fiber Hub: aggregation switch and hosting server of FPGA pre-processor mounted on the rack shelf of networking room at WSEC.

The street site contains an additional SD-DU with UG antennas to support proof-of-concept experiments of UG wireless sensor. The UG SD-DU is based on USRP E312, which is a 2 × 2 MIMO SDR transceiver with an embedded ARM processor and 1Gbps Ethernet port. The underground 2 × 2 MIMO antenna head, as shown in Fig. 4(b), contains 4 patch antenna elements. The center of each element is placed on a square with side of 22.8 cm (9 inch) placed in parallel to the ground plane. The UG antenna head is enclosed by waterproof materials and berried at a depth of 30 cm.

4.2. Fronthaul network

The fronthaul network is based on private high speed Ethernet network running over optical fiber lanes dedicated to the testbed. Dedicated fiber guarantees the bandwidth, latency, as well as security required by the testbed. Ethernet protocol is selected for the convenience of sourcing and management. The fronthaul network contains an aggregation switch, dedicated fibers, and an FPGA pre-processor. Each SD-DU is connected to the aggregation switch to via 2 pairs of 10 Giga bit Ethernet (GbE) fiber. The aggregation switch is also connected to HCC and Internet 2 [19] through 100GbE fibers, respectively. Internet 2 furnishes a 100 Gbit/s network backbone to more than 210 U.S. educational institutions, 70 corporations and 45 non-profit and government agencies, which allows both radio and computing resources of CoSeC-RAN testbed to be directly connected to other testbeds.

The aggregation switch is a Mellanox SN2410 [20], which has 48 × 10/25GbE SFP28 downlink ports and 8 × 100Gbps QSFP28 uplink ports, and is capable of Layer 2 and/or Layer 3 forwarding at 4 Tbps full duplex. This switch can support a total throughput of 100Gbps for the 5 SD-DUs, and is capable of up scaling to more SD-DUs. The model of FPGA pre-processor is BittWare XUPP3R [21], which is a PCIe 16x FPGA card hosted on a rack-mount 4U form server. The FPGA pre-processor is featured with 4 QSFP28 cages, a Xilinx Virtex UltraScale+ VU9P FPGA, and is capable of expanding up to 512GB DDR4 SDRAM. The host server is equipped with a 3.1 GHz Intel Celeron Dual Core CPU, 8GB DDR4 SDRAM, 250GB SSD hard drive, and most importantly, a 850 Watt power module to power the FPGA card. The 4U server is based on operation system of Linux (Ubuntu 18.04 LTS), with Xilinx Vivado Design Suite being installed for FPGA programming. The aggregation switch and FPGA server are mounted on a rack shelf located in Walter Scott Engineering Center (WSEC) as shown in Fig. 5.

The FPGA program of USRP N310 in SD-DU is based on Radio Frequency Network-on-Chip (RFNoC) [22], which is an architecture that connects various modules such as ADC and DAC interfaces, Ethernet core, and other optional Digital Signal Processing modules via AXI bus, as shown in Fig. 6 (left). The paths of digital baseband signal (IQ data) between those modules can be configured from host computers via GNURadio [12]. The native protocol of IQ data over the fronthaul network is UDP-based Virtual Radio Transport (VRT), which is based on VITA-49 [23]) with compressed header (CHDR).

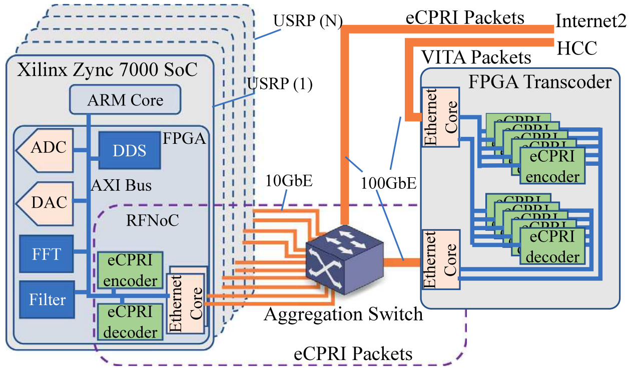


Fig. 6. The schematic of fronthaul logical for eCPRI.

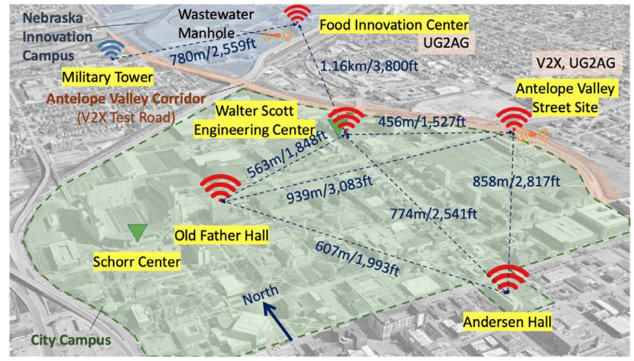


Fig. 7. Site Map (Red: Radio Site, Green: Data Site, Blue: Future Site).

Table 1
Link budget for site-to-site communication (Frequency = 600 MHz).

Tx power	20 dBm [17]
Tx cable insertion loss	1.5 dB
Tx Antenna Gain	6 dBi
Tx Emission Power	$20 - 1.5 + 6 = 24.5$ dBm
Rx Antenna Gain	6 dBi
Required Rx SNR	20 dB
Signal Bandwidth	10 MHz
Thermal noise floor (25 °C)	−103.9 dBm
Rx cable insertion loss	1.5 dB
Receiver noise figure	5.8 dB (@1.8 GHz) [17]
Minimum Detectable Signal	$-103.9 + 5.8 + 1.5 + 20 = -76.6$ dBm
Path Loss Budget	$24.5 - (-76.6) = 101.1$ dB
Tx Rx Antenna Height	20 m
Mean Path Loss at 1000 m	LoS: 88 dB, NLoS: 136 dB [27]

To be further compatible with the fronthaul standard of Cloud-Radio Access Network (C-RAN), customized modules could be added to the FPGA image of USRP N310 to translate the VRT protocol into Common Public Radio Interface over Ethernet (eCPRI) [24]. The FPGA pre-processor co-located with the aggregation switch could then translate eCPRI back to VITA [23] so that the IQ data could be processed by high-performance computing clusters with UHD and GNURadio, as shown in Fig. 6. Moreover, the FPGA pre-processor could also perform high speed digital signal processing (DSP), such as filtering, FFT/iFFT, to offload the baseband processing workload at HCC.

4.3. Cloud-based central unit

The baseband processing and data storage of the CoSeC-RAN take place at the Central Unit (CU) as high-performance computing (HPC) services provided by HCC [8]. Through Virtual Private Network (VPN), researchers could access all the SD-DUs as well as a variety resources including dedicated virtual machine (VM), SLURM [25]-based HPC cluster, Open Science Grid (OSG) [26], and distributed file systems for data and code storage.

For small-scale projects or early prototyping, dedicated VMs on HCC's Anvil private cloud offer researchers full control of the computing resources and software environment. However, connectivity between each SD-DU and VM is limited to a total throughput of 3Gbps and a latency of 2 ms due to current capability and locations of the facilities involved. Direct layer 2 connectivity to each SD-DU is required for certain functions and is achieved by the use of a VPN to which each cloud VM maintains a connection. The use of a VPN is not required in cases where HCC resources can be placed directly on the testbed network segment.

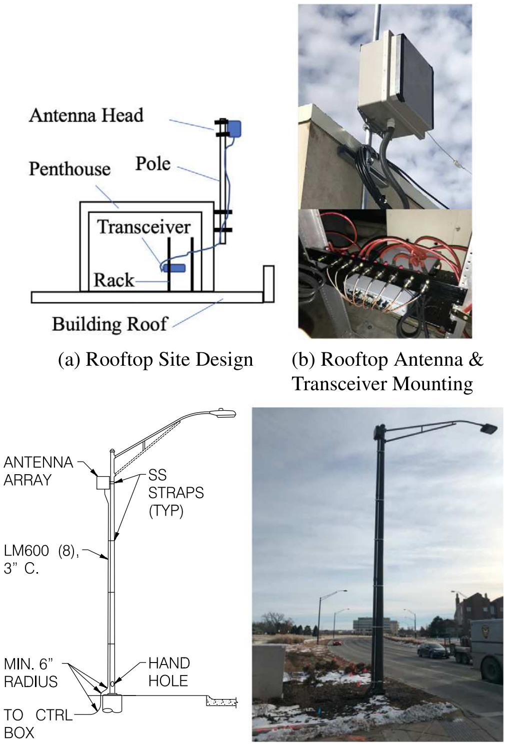
For application that requires online baseband processing and/or high radio bandwidth, the local HCC clusters offer thousands of computing cores with connectivity of up to 10Gbps. The latency between SD-DU and compute nodes is lower than 1 ms with the Rhino cluster co-located with the testbed aggregation switch in WSEC. Researcher could launch applications with tens to hundreds of jobs running in parallel for accessing the air-interfaces of SD-DUs, and online baseband processing based on UHD, GNURadio and/or Matlab. Via the OSG, researchers could run off-line processing in massive parallel (in the order of tens of thousands jobs) with each job limited to 2 h.

For Radio Frequency Machine Learning, the Crane cluster allows researchers to develop applications with jobs accessing the air-interfaces of SD-DUs and CUDA or OpenACC jobs running on GPUs ranging from Tesla K20 to V100S [8]. Moreover, the raw IQ data and/or processing results from user experiments can be stored on HCC for immediate or future usages. The CoSeC-RAN would also become a market of RF data with detailed information of test configurations, where various researchers could publish their data and/or access published data from past experiments for comparing and reproducing existing results. Detailed description of the operation is ignored since it is just standard cloud computing on HPC clusters.

4.4. Site planning and deployment

The locations of the 5 radio sites and 2 data sites as well as line-of-sight (LoS) distances between them are illustrated in Fig. 7, the 3D map of CoSeC-RAN testbed. Four radio sites are deployed on the rooftops of UNL properties. They are Old Father Hall (OFH), Walter Scott Engineering Center (WSEC) and Andersen Hall (AH) on City Campus (light green area), and Food Innovation Center (FIC) on Nebraska Innovation Campus (light blue area). Antelope Valley Corridor, marked as pink area in Fig. 7, is designated for the road test of vehicular to infrastructure (V2I) communications. The street site is located at the intersection of the Antelope Valley Pkwy and Vine street (AVC stands for Antelope Valley Corridor), which belongs to city of Lincoln. The two data sites are the fiber hubs in the basement of WSEC and the office of HCC in Schorr Center. The locations of radio sites are selected with sufficiently separation to reduce the correlation of their spectrum sensing results. On the other hand, the LoS distance between nearest sites is kept below 1km as much as possible so that it is possible to establish a wireless link between two sites. The link budget at a distance of 1km at 600 MHz is illustrated in Table 1. Moreover, an LoS channel within 1km could enable a mmWave link between two sites, to support future mmWave researches. The choice of radio site locations is limited by the availability of penthouse, power supply, fiber connectivity, as well as administrative approval.

The installations of SD-DU at campus and street sites are illustrated in Figs. 8. For campus sites, the antenna head is mounted on a steel pole



(a) Rooftop Site Design (b) Rooftop Antenna & Transceiver Mounting

(c) Street Site Design (d) Street Site Deployment

Fig. 8. Installations of campus and street sites.

installed on the rooftop of selected building, and the SDR transceiver is mounted on rack shelf or cabinet in the penthouse. As a result, SDR transceivers of campus sites are indoors with climate control. The deployed antenna head and rack-mounted SDR transceiver are illustrated in Fig. 8(b). For the street site, the aboveground antenna head is mounted on the top of road light pole (Fig. 8(c)), and SDR transceivers are placed inside a weatherproof enclosure mounted on the traffic signal cabinet next to the pole, as shown in Fig. 8(d). Coaxial cables are running through a conduit mounted outside the pole. The power supply and fiber connectivity of SDR receivers come from the traffic signal cabinet. The UG antenna head is berried 5 ft next to the cabinet. Additionally, temperature sensors, Ethernet-switched power outlet, heaters, and edge switch are installed inside the weatherproof enclosure for climate control and remote power cycle.

It is worth to mention that the 5 SD-DUs are all deployed at representative sites of cellular base-stations. In fact, the 4 campus radio sites are co-located with existing cellular base-stations, and the SD-DU on street site is deployed in a similar way of small cells in other streets of downtown Lincoln. Between radio sites, there are a variety of wireless channels. For example, the wireless channels between AH and WSEC, FIC and WSEC, and OFH and AH are LoS or almost LoS. The channels between WSEC and AH is a typical street canyon (17th Street). The channels between AVC and WSEC, and AVC and AH are blocked by many buildings (NLoS). The LoS distance between sites on/near city campus are from 450 to 940 m, with an exception of FIC to WSEC which is 1.16km. In general, this planning enables the CoSeC-RAN testbed to support experiments of 5G network, and sub-6 GHz point-to-point communications. The distance between neighboring sites would allow CoSeC-RAN to further support mmWave communications given corresponding upgrades.

For underground to above-ground communications, the street site provides a wireless channel with a short, LoS distance of about 12 m. On the FIC site, the underground antenna is located inside a wastewater manhole next to the building. Thus, the FIC site provides a UG2AG channel that is NLoS and of greater distance of about 100 m.

5. Scalability

5.1. Frequency domain

The developed testbed can be scaled up in both frequency and spatial domains. To cover more sub-6 GHz frequency bands, it needs to replace the sub-1 GHz antenna head of SD-DU with antennas of other bands. For higher frequencies, additional broadband amplifiers would be required to compensate the larger insertion loss of cable and path loss of wireless channel. Currently, sub-1 GHz broadband transmit amplifiers with output power of 33 dBm at 500 MHz are ready to be deployed. With broadband power amplifiers being installed before the transmit antennas of the SD-DU, it is also possible to enable reliable site-to-site links, thus support the configuration of mesh network topology. In the future, an additional SD-DU site at *Military Tower* (the blue radio site in Fig. 7) will be deployed for experimental mobile mmWave communications and long-distance THz wireless backhaul (X-Haul) between *Military Tower* and Food Innovation Center.

5.2. Spatial domain

The existing fiber network infrastructure available at UNL and the City of Lincoln could allow more sites to be directly added to the testbed. The current capacity of the core site of the fronthaul network is 200 Gbps which can support another 5 SD-DUs. Additional Ethernet switches would need to be purchased to scale beyond that. There are 12 pairs of fibers between the core site and HCC which could support up to 1.2 Tbps fronthaul capacity for a total of 60 SD-DUs without the installation of new fiber lines.

The City of Lincoln provides 3 pairs of extra fiber lines at its traffic signal cabinets on the public street of Antelope Valley Corridor (AVC). One pair of fiber lines can support up to 10 sites equipped with SDR transceivers of 1Gbps connectivity along side AVC for vehicle to infrastructure experiments.

5.3. Spectrum licensing

For the spectrum license, an experimental zone for the coverage of this testbed has been granted by the Federal Communication Commission. For experiments with low transmit power and on the TV white space channels, no license is required. If higher transmit power or in other frequency bands is required, the University of Nebraska's Department of Information Technology Services has helped to obtain an experimental spectrum license, call sign WA3XCD. With this, we can register each project through the FCC's experimental project registration website.

6. Testing and demonstration

6.1. Antenna element performance

The transmit and receive performance of the monopole antenna element of the aboveground UHF antenna array are tested with Keysight Vector Network Analyzer N9923A, and Keysight Spectrum Analyzer N9912A, respectively. the antenna element has the main frequency band of 452–572 MHz, and higher order bands of 1.33–1.52 GHz and 2.05–2.23 GHz. As a result, the antenna is suitable for transmission in TV white space. The reception band of the antenna element covers most of the sub-1 GHz. As shown in Fig. 9, even being placed at the ground floor of an office building, the antenna element is able to pick up all the major sub-1 GHz radio signals, including FM signals (88–120 MHz), terrestrial TV signals, and cellular signals (700–900 MHz), and aircraft transponder signals (1030–1090 MHz).

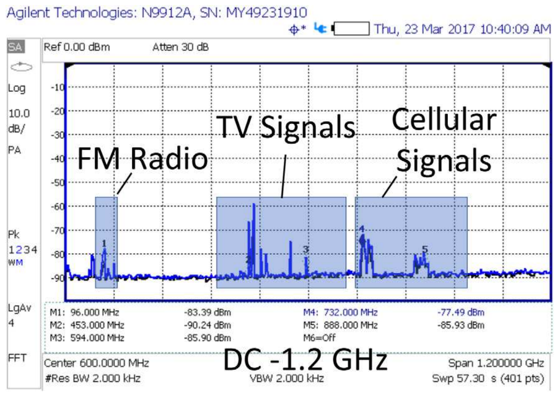
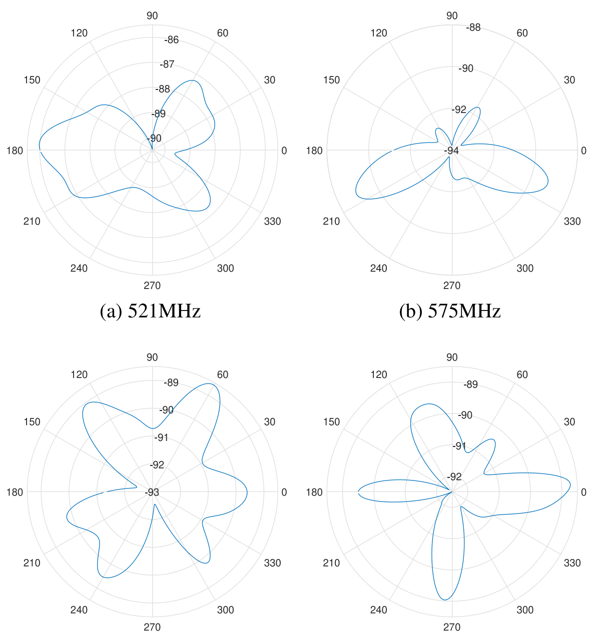


Fig. 9. Receiving spectrum of UHF antenna element in DC-1.2 GHz.



(a) 521MHz (b) 575MHz

(c) 647MHz (d) 659MHz

Fig. 10. Receive beamforming on 2 × 2 uniform rectangular array, H-plane scan of 4 local TV channels with 6 MHz bandwidth, polar axis unit: dBm.

6.2. Receive beamforming

Next, a receiver beamforming scanning on the H-plane is demonstrated. The digital baseband signal (IQ data) of the 2 × 2 uniform rectangular array of the SD-DU at OFH are first collected and saved as files. Then the IQ data files are processed off-line by Matlab MVDR beamformer, and the signal power on H-plane are plotted. The scanning results on 4 local TV channels with 6 MHz bandwidth are illustrated in Fig. 10. The results show strong signal components from multiple directions indicating that the antenna array is placed is a rich multi-path environment. Moreover, the variation of receive signal strength on H-plane is up to 4–6 dB, which shows a good directivity of the UHF antenna array.

6.3. Distributed spectrum sensing

In this demonstration, a GNURadio program simultaneously receives IQ data from the first antenna of all the 5 sites, and displays the spectra-temporal patterns of the spectrum via waterfall plot. The frequency band of the sensing is from 433 to 435 MHz, which covers a ISM band divided into many narrow channels. The real-time distribute spectrum sensing results with a duration of 4 s is presented in Fig. 11 as waterfall plot (above) and instantaneous spectrum (below). The result shows several strong narrow-band signals between 433–433.6 MHz that are picked up by all the 5 sites with different strengths. There are also wider signals centered on 434.62 MHz picked up by 3 sites except AH, and was cut off at the same time (−2.5 s) on FIC, WSEC, and OFH.

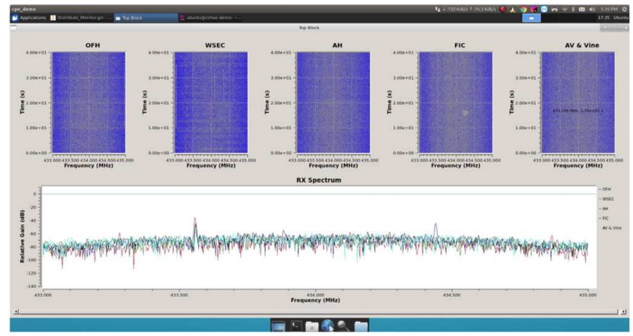


Fig. 11. Waterfall Plot (above) and spectrum (below) of 433–435 MHz band on 5 campus radio sites.

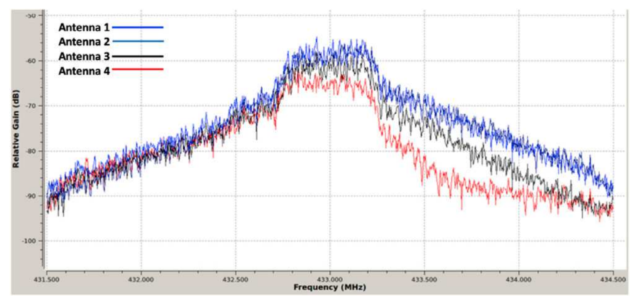
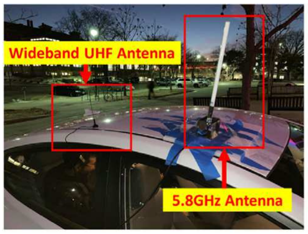


Fig. 12. The Spectrum of received OFDM signal on 4 antennas in underground to aboveground communication test.

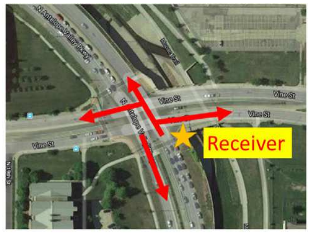
6.4. Underground to above-ground communication

Wireless underground communication is an enabling technology for emerging application including environment and infrastructure monitoring [28], border patrol [29], and precision agriculture [30,31]. With the SD-DU of the street site, we demonstrate the Wireless underground to aboveground (UG2AG) communication in UHF band. A wideband underground patch antenna is buried at depth of 30 cm in the soil and connected to a USRP E312 SDR transceiver in the nearby cabinet. The AG antenna head is about 7 meters aboveground, and connected to USRP N310 SDR transceiver. The distance between the UG and AG antennas are about 10 meters.

OFDM signal with BPSK modulation, 500 kHz bandwidth, transmit power of 15 dBm, and center frequency of 433 MHz is transmitted from the UG antenna to the AG antenna head, as shown in Fig. 8(d). The spectrum of received signal on 4 receive antennas are shown in Fig. 12. The soil causes high attenuation to the signal such that the receive signal strength is only 30 dB above the noise floor, which is too weak to synchronize and demodulate. This experiment shows that UG2AG channel is more challenging than over-the-air channel. Higher transmit power, advanced modulation and waveform design, and processing techniques such as receive beamforming could be employed to improve the performance.

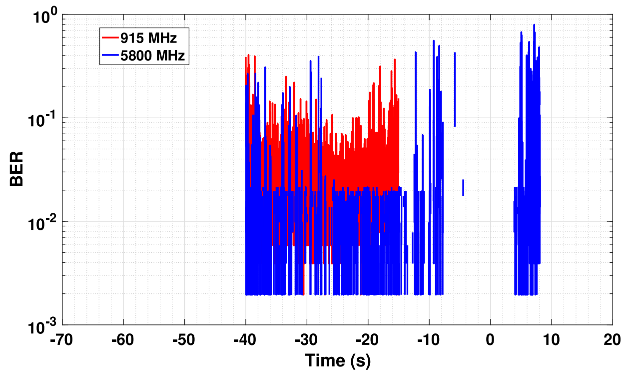


(a)

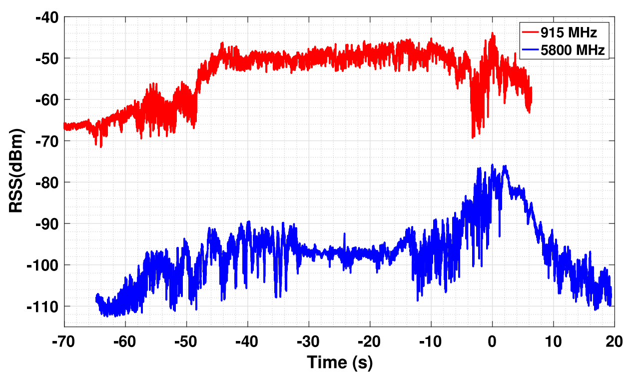


(b)

Fig. 13. V2I communication test setup: (a) vehicular antennas (b) test routes.



(a)



(b)

Fig. 14. Test results of V2I communication test at 915 MHz and 5.8 GHz on single receive antenna: (a) BER (b) RSS. Route from south to north. Time 0s marks the moment the vehicle passing by the road light pole of the receiver antenna.

6.5. Vehicle to infrastructure communication

Vehicle-to-Infrastructure (V2I) communication plays a key role in improving the safety of smart transportation system. With a sedan car, we carried out a V2I communication test at the intersection of Antelope Valley parkway and Vine street using the SD-DU at the street site. A wideband UHF antenna and a 5.8 GHz antennas are mounted on the rooftop of the sedan vehicle, as shown in Fig. 13(a), and a SDR transmitter USRP B200 is placed inside the vehicle. OFDM signal with 30 dBm power, 500 kHz bandwidth, FFT size of 64 and cyclic prefix of 128 is transmitted from the vehicular antenna to the SD-DU at the street site during driving by. The driving by route and location of receiver are shown in Fig. 13(b). OFDM signals are transmitted on center frequencies of 915 MHz and 5.8 GHz in two experiments, in which the vehicle travels in four different directions at the intersection.

During the test, the vehicle was stopped for a red light signal at the intersection before passing by the receiver. We use least squared channel equalizer at the receiver and got the bit error rate (BER) and RSS for 90 s in Figs. 14(a) and 14(b), respectively. The time 0s marks the moment the vehicle passing by the receiver antenna. The gaps on the BER curves stand for frames being dropped due to unable to synchronize. Due to the higher noise figure of the amplifier for 915 MHz as well as higher noise floor, the average BER of 5.8 GHz is 0.0079, which is better than BER of 0.0262 at 915 Mhz. On average, the RSS at 915 MHz is about 50 dB stronger than that at the 5.8 GHz, which is mainly due to the fact that the receiver antenna is for UHF band other than 5.8 GHz band. The vehicle stopped for red light from −40s to −10s for the 915 MHz test, and from −30s to −18s for 5.8 GHz test. RSS is related to the distance between the transmitter and the receiver. Compared to earlier results of V2I test in [32], in which the receiver antenna is placed at lower height of 80 cm and 180 cm, the receive antenna height in this test is 7 m. The BER results of this test and in [32] both fall in similar range between 10^{-2} and 10^{-1}. This experiment demonstrate the capability of this testbed in vehicular to infrastructure communications.

6.6. Education

Besides aforementioned experiments, the CoSeC-RAN testbed is being used in Wireless Communication Networks class for senior and graduate students for education in wireless communication principles, network experimentation, and spectrum sensing during their course projects and labs. The students created several innovative projects, such as: using the testbed to collect aircraft transponder signals, identifying mobile device locations, collection of weather broadcast data, etc.

7. Conclusion

In this paper, a city-wide testbed, CoSeC-RAN, equipped with latest high-end SDR transceivers and cloud computing facilities, is presented. Its functionalities are demonstrated via basic spectrum sensing operations, including receive beamforming and distributed spectrum sensing. This testbed is based on an architecture of Cloud-Radio Access Network, with advanced computational resources, rich environmental variety, and scalability. It could facilitate researches in Dynamic Spectrum Access, 5G, Internet of Advanced Things, Vehicular Networks, and Radio Frequency Machine Learning for the next generation wireless networks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was partly supported by National Science Foundation, USA, under grants CNS-1731833, CNS-1816938, and CNS-1619285.

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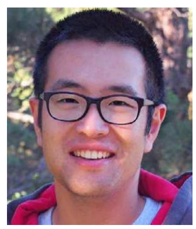
Zhongyuan Zhao received his B.Sc. and M.S. degrees in Electronic Engineering from the University of Electronic Science and Technology of China, Chengdu, China, in 2006 and 2009, respectively. He received his Ph.D. degree in Computer Engineering from the University of Nebraska-Lincoln, Lincoln, NE, in 2019, under the guidance of Prof. Mehmet C. Vuran. From 2009 to 2013, he worked for ArrayComm and Ericsson, respectively, as an engineer developing 4G base-station. Currently, he is a postdoctoral research associate at the Department of Electrical and Computer Engineering of Rice University. Dr. Zhao's current research interests focus on machine learning for wireless networks.

Mehmet Can Vuran was born in Istanbul, Turkey. He received his B.Sc. degree in Electrical and Electronics Engineering from Bilkent University , Ankara, Turkey in 2002. He received his M.S. and Ph.D. degrees in Electrical and Computer Engineering from the Broadband and Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA. in 2004 and 2007, respectively, under the guidance of Prof. Ian F. Akyildiz. Currently, he is the Susan J. Rosowski Professor of Computer Science and Engineering at the University of Nebraska-Lincoln. Dr. Vuran was awarded an NSF CAREER award for the project "Bringing Wireless Sensor Networks Underground". He is a Daugherty Water of Food Institute Fellow.



Baofeng Zhou received his B.E. in Electronic Information Science and Technology from the School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing, China, in 2015. Currently, he is a graduate research assistant and pursuing his Ph.D. degree in Computer Engineering in the Cyber–Physical Networking Laboratory, Department of Computer Science and Engineering, University of Nebraska-Lincoln, Lincoln, NE, under the guidance of Prof. Mehmet C. Vuran. His current research interests include the Internet of Things, agricultural IoT, wireless underground communications, and advanced clock synchronization for IoT.

Mohammad Mosiur Rahman Lunar is a Ph.D. student in the Department of Computer Science and Engineering at the University of Nebraska-Lincoln. He is working as a research assistant in the Cyber–Physical Networking Lab under the supervision of Professor Mehmet Can Vuran. He is currently working in Vehicle-to-Barrier (V2B) networking project for his Ph.D. Prior to starting his Ph.D., Lunar finished his bachelor's degree in Electrical and Electronic Engineering from Bangladesh University of Engineering and Technology. He also worked as an engineer in the R&D division at Kona Software Lab.

Zahra Aref received her M.Sc degrees in electrical engineering from Isfahan University of Technology, Isfahan, Iran, in 2014. She was a lecturer at Shahab Danesh University and Qom University from 2013 to 2017. She studied in the Department of Computer Science and Engineering at the University of Nebraska-Lincoln in 2018. Currently, Zahra Aref is pursuing her Ph.D. degree in the Department of Electrical and Computer Engineering at Rutgers University, New Jersey, United States.

David P. Young received his B.Sc in business administration and management and M.Sc. in telecommunications management from Oklahoma State University, Stillwater, OK, in 2006 and 2012, respectively. He served for the City of Lincoln as fiber infrastructure and right of way manager since 2012 and is now the chief information officer since 2019, respectively. Since 2018, David Young serves on the Broadband Deployment Advisory Committee of the Federal Communications Commission.

Warren Humphrey received his B.Sc in electrical engineering from University of Nebraska-Lincoln in 1991 and M.Sc in engineering management from The University of Kansas in 1993, respectively. From 1993 to 1997, he worked for Black & Veatch as instrumentation and control engineer. From 1997 to 2001, he served for Sega Inc. as control system engineer. He joined Olsson, Lincoln, NE, since 2001, and currently serves as the vice president of Olsson.

Steve Goddard received his B.A. degree in computer science and mathematics from the University of Minnesota, Duluth (1985) and the M.S. and Ph.D. degrees in computer science from the University of North Carolina at Chapel Hill (1995, 1998). He is Dean of the College of Liberal Arts and Sciences at the University of Iowa where he holds the UI Alumni Association Dean's Chair. Prior to joining the faculty at Iowa in 2019, Goddard was the John E. Olsson Professor of Computer Science & Engineering at the University of Nebraska-Lincoln (UNL) and served in multiple administrative roles there, including Vice Chancellor for Research, Dean and Department Chair. Prior to joining the faculty at UNL, Dr. Goddard worked in the computer industry for 13 years, including nine years as president of his own company.

Garhan Attebury received his B.Sc in computer science from Eastern Oregon University in 2004, and M.Sc. in computer science from University of Nebraska-Lincoln in 2006. Since 2006, he has been working for University of Nebraska-Lincoln as system administrator. Currently, he is the lead system administrator at the Holland Computing Center, University of Nebraska-Lincoln.

Blake France received his B.Sc. degrees in management and information technology, respectively, from University of Nebraska-Lincoln, in 1994. Since 1994, he has been working for University of Nebraska-Lincoln as project manager at the Department of Information Technology Service.