A City-Wide Experimental Testbed for Next Generation Wireless Networks

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***Abstract*—A city-wide experimental testbed is developed to facilitate the research of dynamic spectrum access, 5G, underground wireless communications, and Radio Frequency Machine-Learning in real-world environments. This testbed is composed of 5 cognitive radio sites, and covers 1.1 square miles across two campus of University of Nebraska-Lincoln and a public street in the city of Lincoln, NE. Each site is equipped with a 4x4 MIMO software-defined radio transceiver, USRP N310, with 20Gbps fronthaul connectivity. Moreover, the street site contains an additional cognitive radio transceiver with underground 2x2 MIMO antenna. The testbed has FPGAs at both the edge and fronthaul network, and a cloud-based central unit, where data processing and storage take places. Developed based on collaboration of the university, city, and industrial partners, this testbed will facilitate education and researches in academic and industrial communities.**

***Index Terms*—Dynamic Spectrum Access, Internet of Advanced Things, Spectrum Sensing, Radio Frequency Machine Learning, Underground Radio, USRP**

I. 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 [3], [4], [8], [10], [11] 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 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 environments, standardized experimental configurations, reusable datasets, as well as advanced computational resources.

To address aforementioned requirements, a pilot city-wide testbed, Cognitive Secure Cloud-Radio Access Network (CoSeC-RAN) is developed with collaboration with the City of Lincoln in this paper. CoSeC-RAN pilot 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 connected to cloud-based central unit via 20Gbps fronthaul network, and is equipped a sub-6GHz Software-Defined Radio (SDR) transceiver and a 4x4 MIMO antenna array. Additionally, the street SD-DU is further equipped with underground (UG) MIMO antennas for researches of underground wireless sensors. The CoSeC-RAN pilot has rich computational resources. FPGAs are available at the SD-DUs

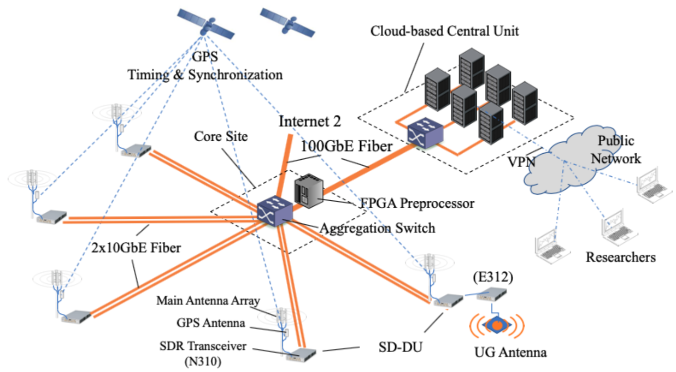


Fig. 1. CoSeC-RAN Pilot Testbed Architecture.

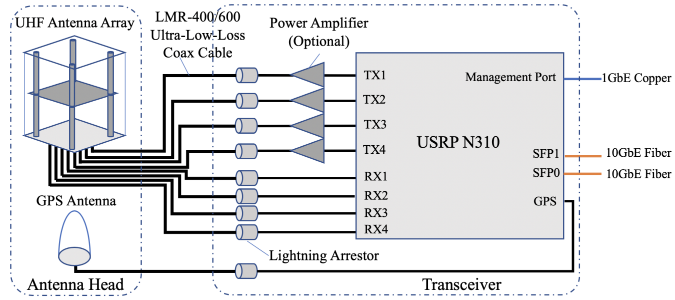


Fig. 2. Software Defined Distribution Unit Schematic.

and fronthaul network. An array of Graphics processing units (GPUs) are available in the cloud computing facilities. Projects at various scales and stages could be supported by a variety of general cloud computing resources, such as dedicated virtual machine, high-performance clusters.

II. Related Work

Notable early initiatives of cognitive radio testbeds include WARP platform [2] from Rice University, and CORNET [3] and LTE-CORNET [4] from Virginia Tech. WARP provides a series 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 [5], typical SDR hardwares are USRP [6], WARP [2], and popular software are GNURadio [7], LabView, and Matlab, where the combination of USRP and GNURadio is most popular.

FIT [8] 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) [9] is another initiative of large-scale open testbeds supported by National Science Foundation in the U.S.. Two testbeds were approved: POWDER-RENEW [10], 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 [11].

Similar to the first two PAWR projects [10], [11], the CoSeC-RAN pilot 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. CoSeC-RAN pilot testbed targets sub-6GHz frequencies, and is currently focused on sub-1GHz. Moreover, this testbed support underground wireless researches in UHF band, and can be extended to mmWave radio communications.

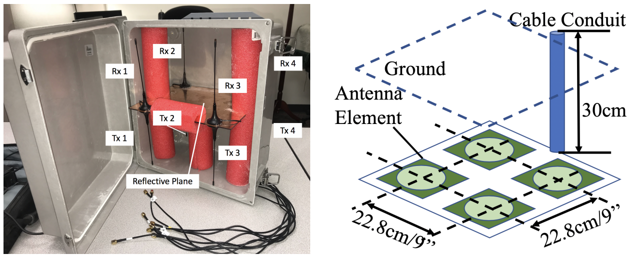
III. Testbed Implementation

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), is based on a high-end 4x4 MIMO Software Defined Radio (SDR) Transceiver that can be tuned to any sub-6GHz frequency. Currently, there are 5 SD-DUs on 4 campus sites and 1 street site. All the SD-DUs are connected to Holland Computing Center (HCC) [12] 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. More detailed implementation of the testbed are introduced as follows.

A. *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. 2. The core of SD-DU is a high-end Software Defined Radio (SDR) transceiver, Universal Software Radio Peripheral (USRP) N310 [13]. The N310 has 8 RF ports: 4 transmit (Tx) and 4 receive (Rx) channels. Each channel provides up to 100MHz of instantaneous bandwidth, and covers a frequency range from 10MHz to 6GHz. The maximum output power of Tx port is 12-18dBm [13].

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 1.2/0.6dB at 600MHz and 3.2/1.6dB at 2.4GHz for a length of 50ft. For each site, the 8 coaxial cables are made with the same length. At different sites, the cable length varies from 25 to 50ft. A 3.3V active GPS antenna [14] 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



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

Fig. 3. UHF Antenna Array: 2x2 Uniform Rectangular Array.

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-6GHz. Therefore, an UHF antenna array for sub-1GHz band is designed, as shown in Fig. 3(a). The antenna element is an off-the-shelf omnidirectional monopole antenna with a gain of 6dBi, which is originally used in USB TV dongles. The UHF antenna array, as shown in Fig. 3(a), contains two 2x2 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 428MHz radio wave, $\lambda/2$ of 856MHz, where λ denotes the wavelength of electromagnetic wave in the atmosphere. Thus, this UHF antenna array is capable of beamforming from 428 to 856MHz without grating lobes.

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 $2{\times}2$ MIMO SDR transceiver with an embedded ARM processor and 1Gbps Ethernet port. The underground 2x2 MIMO antenna head, as shown in Fig. 3(b), contains 4 patch antenna elements. The center of each element is placed on a square with side of 22.8cm (9 inch) placed in parallel to the ground plane. The UG antenna head is enclosed by waterproof materials and berried at a depth of 30cm.

B. Fronthaul Network

The fronthaul network is based on private high speed Ethernet network running over dark fibers dedicated to this project. Dark 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 optical fiber lanes (dark fiber), 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 [15] through 100GbE fibers, respectively. Internet 2 allows both radio and computing resources to be directly connected to other testbeds.

The model of aggregation switch is EdgeCore AS5914-54X [16], which has $48{\times}$10GbE SFP+ downlink ports and $6{\times}$100Gbps QSFP28 uplink ports, and is capable of Layer 2 and/or Layer 3 forwarding of 2.1 Tbps full duplex. This switch can support a total throughput of 100Gbps for the

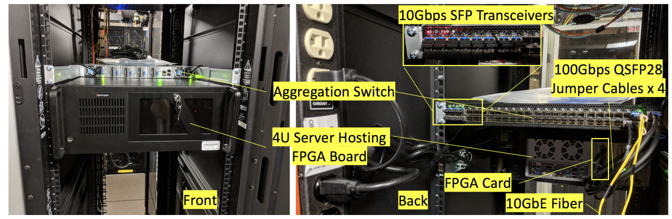


Fig. 4. Fiber Hub: Aggregation Switch and Hosting Server of FPGA Pre-processor mounted on the rack shelf of networking room at SEC.

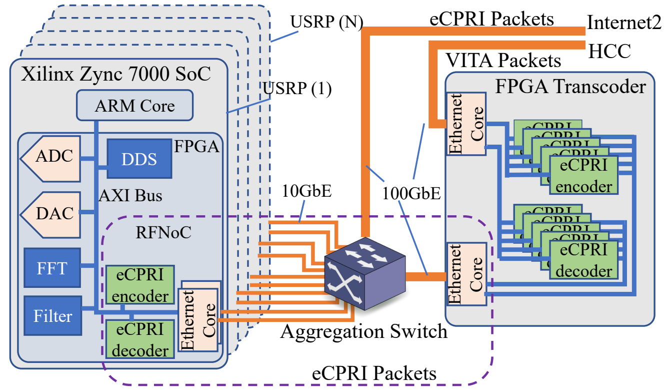


Fig. 5. The Schematic of Fronthaul Logical for eCPRI.

5 SD-DUs, and is capable of up scaling to more SD-DUs. The model of FPGA pre-processor is BittWare XUPP3R [17], 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 3.1GHz 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 16.04 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 Scott Engineering Center (SEC) as shown in Fig. 4.

The FPGA program of USRP N310 in SD-DU is based on Radio Frequency Network-on-Chip (RFNoC) [18], 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. 5 (left). The paths of digital baseband signal (IQ data) between those modules can be configured from host computers via GNURadio [7]. The native protocol of IQ data over the fronthaul network is UDP-based Virtual Radio Transport (VRT), which is based on VITA-49 [19]) with compressed header (CHDR). 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) [20]. The FPGA pre-processor co-located with the aggregation switch could then translate eCPRI back to VITA [19] so that the IQ data could be processed by high-performance computing clusters with UHD and GNURadio, as shown in Fig. 5. 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.

C. 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 Holland Computing Center (HCC) [12]. Through Virtual Private Network (VPN), researchers could access all the SD-DUs as well as a variety resources including dedicated virtual machine (VM), SLURM [21]-based local cluster, and Open Science Grid (OSG) [22], and a distributed file system for data and code storage.

For small-scale project or early prototyping, the best option is the dedicated VM on Anvil, of which researchers have full control of the computing resources and software environment. However, the connectivity between each SD-DU and VM is limited to a total throughput of 3Gbps and a latency of 2ms due to current capability and locations of the facilities.

For application that requires online baseband processing and/or high radio bandwidth, the local clusters offer thousands of computing nodes each with connectivity of 10Gbps. The latency between SD-DU and each node could be lower than 1ms on Sandhills cluster co-located with the HCC gateway (Schorr Center). 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 OSG, researchers could run off-line processing in massive parallel (in the order of tens of thousands jobs) with each job limited to 2 hours.

For Radio Frequency Machine Learning, clusters Crane and Tusker allow researchers to develop applications with jobs accessing the air-interfaces of SD-DUs and CUDA or OpenACC jobs running on GPUs of Tesla K20 to P100 [12]. 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.

D. Site Planning and Deployment

The locations of 5 radio sites and 2 data sites of CoSeC-RAN pilot testbed are marked in Fig. 6, with the line-of-sight (LoS) distance between radios sites being labeled. 4 radio sites are deployed on the rooftops of campus buildings at UNL. They are Old Father Hall (OFH), Walter Scott Engineering Center (WSEC) and Andersen Hall (AH) on City Campus, and Food Innovation Center (FIC) on Nebraska Innovation Campus. The street site is located at the Antelope Vally Pkwy and Vine street (AVC stands for Antelope Valley Corridor), which belongs to city of Lincoln. The two data sites are the fiber hub in the basement of WSEC, and the office of HCC in Schorr Center. The locations of radio sites are selected

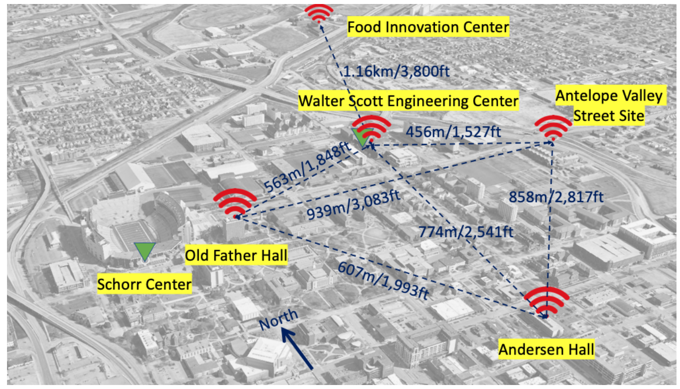


Fig. 6. Site Map (Red: Radio Site, Green: Data Site).

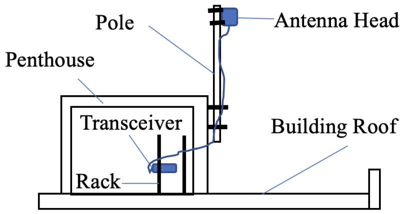
Table I. Link Budget for Site-to-Site Communication (Frequency = 600MHz)

Tx power	20 dBm [13]
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 (@1.8GHz) [13]
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 meters
Mean Path Loss at 1000m	LoS: 88 dB, NLoS: 136 dB [23]

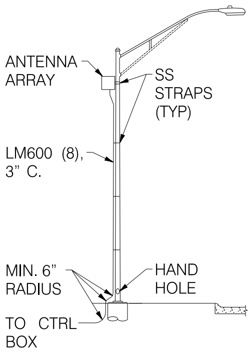
with sufficiently separation to reduce the correlation of their spectrum sensing results. On the other hand, the LoS distance between nearest sites is kept below 1km as much as possible so that it is possible to establish a wireless link between two sites. The link budget at a distance of 1km at 600MHz is illustrated in Table. I. 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. 7. For campus sites, the antenna head is mounted on a steel pole installed on the rooftop of 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. For the street site, the aboveground antenna head is mounted on the top of road light pole (Fig. 7(b)), and SDR transceivers are placed inside a weatherproof enclosure mounted on the traffic signal cabinet next to the pole, as shown in Fig. 7(c). 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 5ft 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



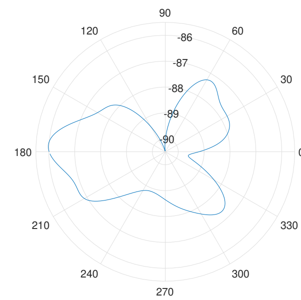
(a) Campus Building Rooftop Installation



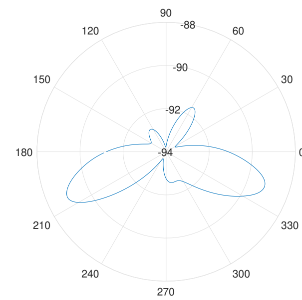
(b) Street Site Design

(c) Street Site Deployment

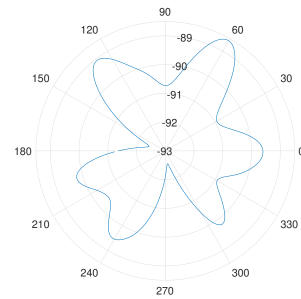
Fig. 7. Installations of Campus and Street Sites.



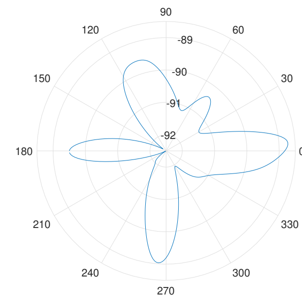
(a) 521MHz



(b) 575MHz



(c) 647MHz



(d) 659MHz

Fig. 8. Receive Beamforming on 2x2 Uniform Rectangular Array, H-Plane Scan of 4 Local TV Channels with 6MHz bandwidth, Polar axis unit: dBm.

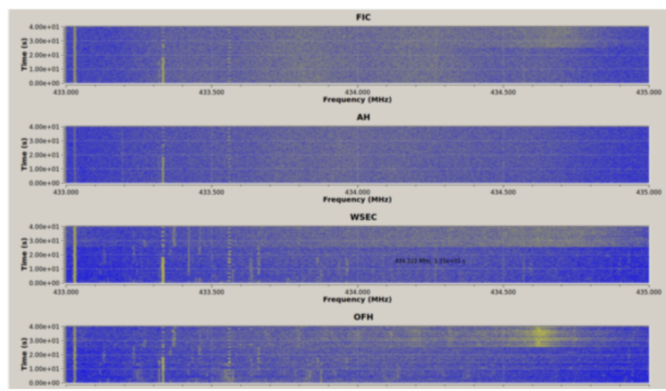


Fig. 9. Waterfall Plot of 433-435MHz Band on 4 Campus Radio Sites.

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 meters, with an exception of FIC to WSEC which is 1.16km. In general, this planning enables the NEXT pilot testbed to support experiments of 5G network, and sub-6GHz point-to-point communications. The distance between neighboring sites would allow CoSeC-RAN to further support mmWave communications given corresponding upgrades.

IV. Testing and Demonstration

A. Antenna Element Performance

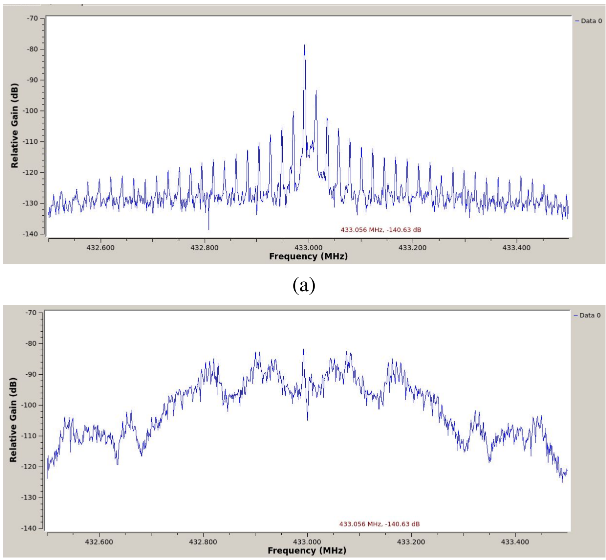
The transmit and receive performance of the monopole antenna element of the aboveground UHF antenna array are tested with Keysight Vector Network Analyzer N9923A, and Keysight Spectrum Analyzer N9912A, respectively. The antenna element has the main frequency band of 452-572 MHz, and higher order bands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

B. Receive Beamforming

Next, a receiver beamforming scanning on the H-plane is demonstrated. The digital baseband signal (IQ data) of the 2x2 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 6MHz bandwidth are illustrated in Fig. 8. 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 4-6dB, which shows a good directivity of the UHF antenna array.

C. Distributed Spectrum Sensing

In this demonstration, a GNURadio program simultaneously receives IQ data from the first antenna of all the 4 campus



(a)

(b)

Fig. 10. The Spectrum of Received Signal in Underground to Aboveground Communication: (a) Transmitter Muted, (b) BPSK Signal Transmitted.

radio 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 seconds is presented in Fig. 9. The result shows several strong narrow-band signals between 433-433.6MHz that are picked up by all the 4 sites with different strengths. There are also wider signals centered on 434.62MHz picked up by 3 sites except AH, and was cut off at the same time (-2.5sec) on FIC, WSEC, and OFH.

D. Underground to Aboveground Communication

In this demonstration, the BPSK signals with 1MHz bandwidth and center frequency of 433 MHz is transmitted from the underground antenna to the aboveground antenna at the Street site. The spectrum of received signal when the transmitter is muted and when BPSK signal is transmitted are shown in Figs. 10(a), and 10(b), respectively. When BPSK signal is muted, there is only local oscillator leakage in the spectrum at the receiver, which is distinct from the spectrum of received BPSK signal when the transmitter is on. The dynamic range of the received signal in this demonstration is over 40dB.

V. Conclusion

In this paper, a city-wide testbed, CoSeC-RAN pilot, 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 pilot 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, and Radio Frequency Machine Learning for the next generation wireless networks.

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