

## PAWR Platform Full Proposal: NEXTT: Nebraska Experimental Testbed of Advanced Things

### Section I Platform Vision

The **Nebraska Experimental Testbed of Advanced Things (NEXTT)** will leverage an established urban public-private deployment of fiber and wireless infrastructure and the largest U.S. network of agricultural producers to enable wireless breakthroughs for new Internet of Advanced Things (IoAT) scenarios (Fig. 1) via *an IoAT network platform with densities as high as 40 sites and a network diameter of as large as 200 miles*.

NEXTT will: (1) address unique **public safety, infrastructure, smart agriculture,** and **rural broadband connectivity** needs via a *seamless wireless continuum* across underground and over-the-air and urban and rural settings to bridge the digital divide; (2) facilitate transdisciplinary research to address IoAT challenges as PAWR's IoAT research platform; (3) provide a comprehensive infrastructure and RF waveform database to test and verify new IoAT theories, tools, and technologies while complementing existing PAWR networks; (4) work collaboratively with local government and utility operators, attract users, and enhance public-private partnerships; and (5) increase national competence across scientific fields to rapidly bring new technologies to Urban and Rural end users alike. The University of Nebraska-Lincoln (UNL) and City of Lincoln (Lincoln) lead NEXTT in partnership with Olsson Corp. (Olsson); Georgia Institute of Technology (GT); the Ohio State University (OSU); University at Buffalo (UB); Renaissance Computing Institute (RENCI); NASA Jet Propulsion Laboratory (JPL); Allo Communications (Allo); Lincoln's police, fire, transportation, and utilities departments; Teledyne Instruments (Teledyne); Valmont; Bayer Crop Science (Bayer); Small Data Tech (SDT); NebraskaLink; Don't Panic Labs (DPL); and other private and public entities.

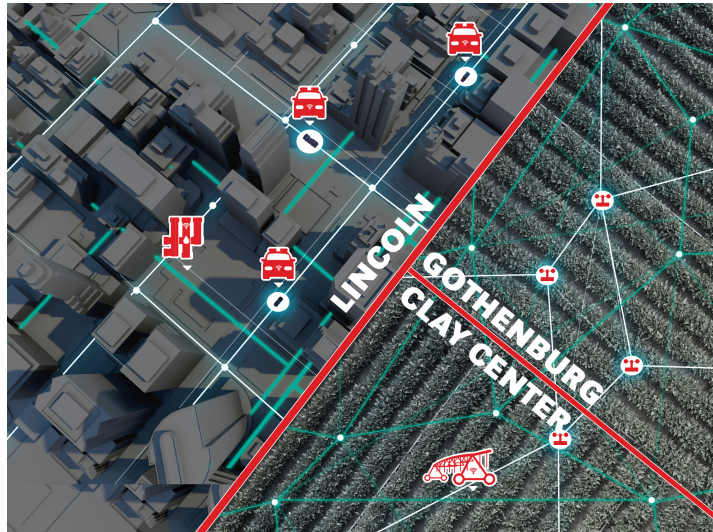


Figure 1: *NEXTT-enabled community usage scenario.*

#### I.1 Use Cases

While today's Internet of Things applications bring new requirements to the evolving wireless standards, tomorrow's advanced use cases will *drive* these innovations through Internet of *Advanced* Things (IoAT). In NEXTT's first retreat in summer 2018, more than 40 public, private, and academia representatives worked together to identify three IoAT use cases as shown in Fig. 1:

 **Real-time Police Dash and Body-worn Camera Video Streaming.** While real-time video streaming has tremendous potential for crime scene investigation and emergency medical services, a technological leap forward in wireless uplink communication rates coupled with resilient high mobility connections is needed to fully realize the value of the technology. Current solutions (Fig. 2(a)-2(b)) incur days of delay for data to upload via a WLAN or physical connection. Further, body mounted devices can be lost during a foot chase, run over, or shot, resulting in loss of evidence. The only solution against such loss is to offload evidence quickly via new technology breakthroughs that can deliver high uplink bandwidth in real-time with low power consumption. Real-time body, head, and dash cam video delivery, coupled with machine learning solutions, can help detect use of force, improve officer safety, detect policy violations, and alert dispatch for help. To enable these and future public safety use cases, technology breakthroughs in wireless communications are needed. NEXTT will leverage mobile mmWave communications for Lincoln Police Department (LPD) and WatchGuard body and dash camera

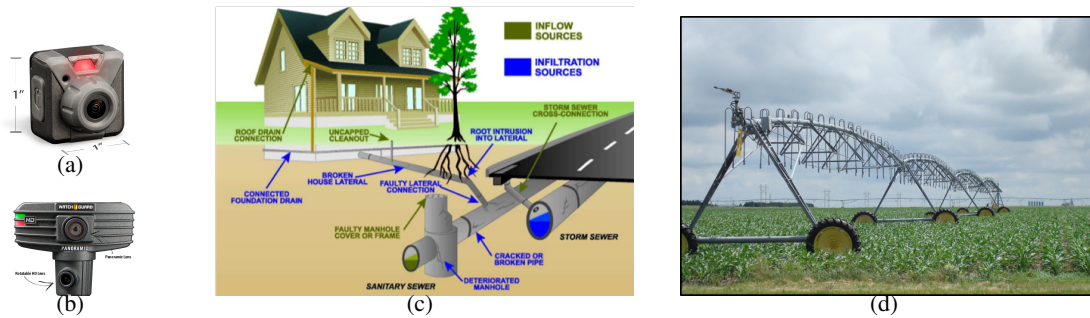


Figure 2: (a) *Body* and (b) *dash* cams (Credit: WatchGuard); (c) *in-flow and infiltration in sewage systems* (Credit: Teledyne); (d) *A 4-span variable rate irrigation center pivot system established by Co-PI Irmak* (Credit: Irmak, 2009).

systems to develop real-time video streaming applications.

**Urban Underground Infrastructure Monitoring.** Lincoln has more than \$1B public underground infrastructure with an annual maintenance budget of \$32M. As with most communities, its sanitary and storm sewer systems suffer from increased flow volume and aging infrastructure, which results in basement backups, manhole overflow, and discharge of untreated water into local waters (Fig. 2(c)). Because sewer networks are underground, it is challenging to take preventive action to avoid these risks, and most communities implement temporary programs to inspect and document pipe condition. Unfortunately, required equipment for such programs is expensive and manpower intensive. Real-time underground telemetry would enable communities to proactively take corrective action to mitigate undesired situations and manage the upkeep cost of the network. Current underground IoAT solutions are rare due to connectivity challenges and extensive cabling costs. Partnering with Lincoln's Wastewater System (LWWS) and Teledyne, NEXTT will enable transformative urban underground IoAT applications (e.g., real-time flow monitoring, intrusion and infiltration (I&I) isolation, and smart manhole lids). Coupling real-time I&I and water quality sensors with advanced underground wireless connectivity will revolutionize wastewater and stormwater management in Lincoln and around the world.

**Real-time Soil Monitoring and Irrigation Automation.** While soil moisture measurements have informed irrigation decisions for decades (Fig. 2(d)), real-time measurement and automated irrigation solutions still face challenges (e.g., lack of robust rural wireless coverage and difficulty installing and removing sensors before and after a growing season). The need for real-time in-situ information from large and diverse agricultural fields has given rise to ***Agricultural Internet of Advanced Things (Ag-IoAT)***, which could provide in-situ monitoring capabilities (e.g., soil moisture, temperature, electrical conductivity) and, when interconnected with existing field machinery (seeders, irrigation systems, sprayers, combines), enable field autonomy, paving the way for better food production solutions [99]. According to Valmont, one of the biggest challenges facing precision agriculture is getting information to growers and enabling them to take action. Progress depends on a system of in-field sensors, aerial or satellite imagery, communication devices, cloud-based analytics, remote monitoring, and real-time control of in-field equipment. A high-bandwidth, wide-area network with good penetration of foliage, buildings, and terrain is needed to remedy the weak or nonexistent bandwidth and coverage in rural areas. Currently, Bayer, which acquired Monsanto, including its precision Ag subsidiary Climate Corporation, creates high-resolution integrated data sets at large scale and brings them into models that provide data-driven insights for the specific needs of customers, farms, crops, and soil. However, scalable and timely access to the high-resolution field data, which currently Bayer R&D projects and ultimately farmers demand, is a challenge. Timely and high-resolution insights into soil characteristics have been challenging due to the difficulty of seasonal installation and removal of soil sensor systems, along with the lack of cost effective and high performing data acquisition. Advanced underground wireless sensors, coupled with high capacity, reliable THz wireless networks for transfer of data to processing centers, will be game-changing. NEXTT will partner with Valmont and Bayer to utilize advanced in-field underground wireless connectivity for permanent soil sensors. Coupled with the newly developed, reliable, high bandwidth wireless connectivity in rural communities, these systems will contribute significantly to the adoption of technology in production.

## I.2 Required, Transformative, Enabling Wireless Technologies

Real-time streaming of public safety video, under ground wireless infrastructure sensors, and fully connected Agricultural IoT platforms are plagued by the same set of problems and missing technologies. Crowded frequencies, lack of purpose built radios, and missing fundamental research are holding these advanced use cases back from achieving significant societal impact. A common set of research and technology developments are needed: NEXTT will facilitate breakthroughs in mobile mmWave, hybrid magnetic induction/radio frequency (MIRF) underground communications, and THz backhaul, coupled with a dynamic spectrum sharing (NextGen Radio Access Network) NG-RAN architecture in order for these use cases to reach their full potential.

**Dynamic Spectrum Sharing NG-RAN:** To support heterogenous requirements of IoAT applications, NEXTT elevates back/mid/front-haul utility from a data interconnect to an experimental architecture component and introduces the **X-haul Plane (XHP)** as an RF counterpart to SDN control and data planes. XHP will allow for dynamic designations of back/mid/front-haul functionalities to physical infrastructure for optimal functional splitting. A **NEXTT RF database** for reproducible experimentation similar to a few other fields (e.g., ImageNET [44]) will be created with XHP.

**Mobile mmWave:** NEXTT's energy-efficient mmWave devices based on hybrid beamforming will support real-time, high data-rate communication. The platform combines beam agility for highly directional communication in mobile environments with ultra-low-power characteristics. OSU's novel beam forming, tracking, and resource management [55, 56, 90] approaches will drive hybrid electronically scanned arrays (ESA) operating in mmWave to support user mobility. mmWave small cells will support many nodes in real world high mobility settings by achieving energy-efficient switching speeds in the order of milliseconds. At the user end, mmWave in-car cameras will stream real-time police video, supporting mmWave and video streaming research needs of our users through a realistic vertical. Our proposed mmWave technology complements COSMOS [4] through the introduction of energy-efficient solutions supporting highly mobile end users.

**Hybrid MIRF Wireless Underground:** UNL-patented underground (UG) communication technologies [100] will be augmented with novel high-throughput UG multi-carrier and long-range soil-adaptive UG beamforming solutions [85, 86] for extensive connectivity in underground pipes and crop fields. In addition a unified, hybrid, remotely accessible platform, which integrates GT's magnetic induction (MI) transceivers [77] with UNL's radio frequency (RF) transceivers, will create a new class of hybrid **MIRF UG radios** for UG use cases. Specifically, in underground environments MI can have stable channel qualities regardless of environmental variations, while RF can provide omnidirectional transmission, high data rates, and aboveground connectivity. The main objective of this wireless breakthrough is to bring the synergy of MI and RF technologies to wireless underground applications. This platform will enable novel rural soil moisture and underground infrastructure monitoring, and support wireless communication research in challenging environments.

**THz X-Haul:** THz links will leverage UB and NASA JPL's platform, which recently demonstrated the feasibility of ultra-broadband THz communications over distances expanding more than 1 km (i.e., a **world-record-setting 2.1 km** when transmitting at 2 Gigabits-per-second (Gbps) at 225 GHz). The transmitter and receiver front-ends will be based on NASA JPL proprietary Schottky-diode-based high-power frequency multipliers and broadband mixers, with output power above 100 mW. The digital baseband will be implemented on state-of-the-art FPGAs and incorporate data link and physical layer solutions tailored to the THz frequency band, including channel estimation and equalization; signal modulation and coding; time, frequency and phase synchronization; and resource allocation strategies [52, 53, 68]. The THz X-Haul will provide fiber-optical-like backhaul connectivity to remote areas with minimal installation costs, in which massive data flows resulting from the aggregation of end-user devices and sensing equipment are generated. NEXTT will allow researchers to evaluate the performance of different THz communication strategies in real scenarios, with changing weather conditions and traffic patterns. In addition, researchers can test their own THz transceivers and antennas and the use of THz links for long-range atmospheric and biological sensing will be supported.

**Ag-IoAT and Rural Broadband Connectivity:** Future Ag-IoAT sites will resemble small-cells with intermittent connectivity requirements (e.g., during growing seasons). The existing Ag-IoAT testbed at UNL's

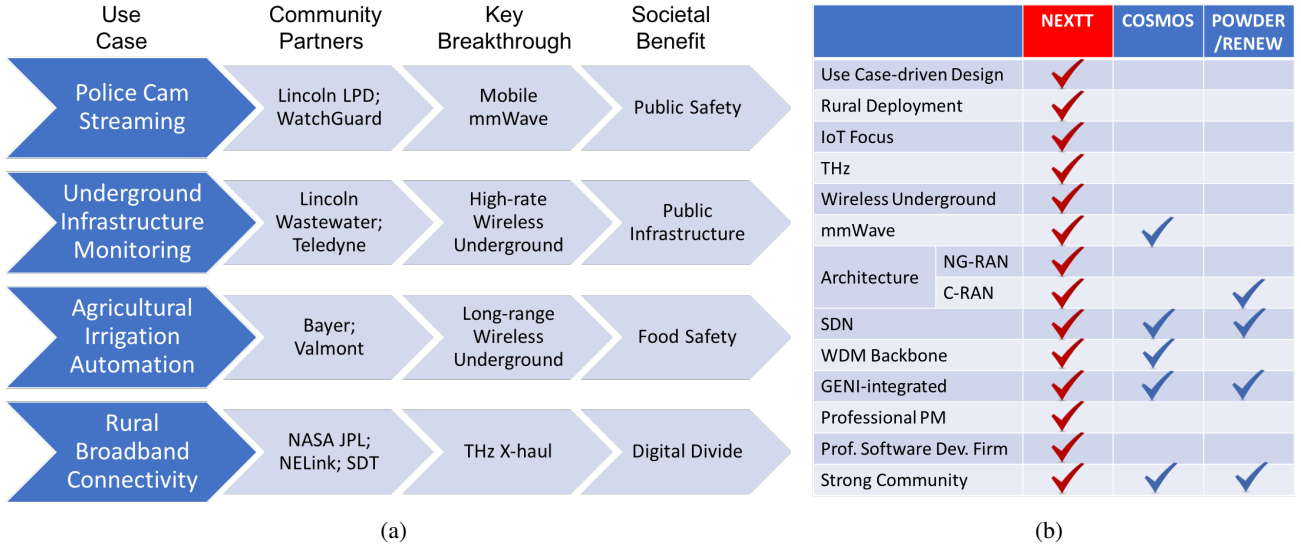


Figure 3: (a) *NEXTT vision* and (b) *NEXTT unique and complementary features within the PAWR Federation*.

South Central Agriculture Lab (SCAL) [92] will be opened to researchers and rural communities to inform public decision-making. SCAL will feature a hybrid Over-the-Air (OTA)-underground radio for an agricultural small cell and serve underground IoT devices. In addition, THz, mmWave, and SigFox/LoRa links will serve five automated weather stations deployed in nearby production fields to engage farmers. Weather variables will be transmitted to decision-makers to support effective farming practices. In addition to SCAL, small cells will be established in Bayer's Gothenburg research fields via fiber-connected THz backhaul. NebraskaLink will leverage fiber access for tower locations and Small Data Tech towers will be equipped with THz radios to support research in rural broadband connectivity.

NEXTT's vision will be enabled through key wireless breakthroughs in THz, hybrid wireless underground, and mmWave technologies, supported by an NG-RAN architecture, that will impact a large array of beneficiaries in public safety, public infrastructure, food safety, and rural connectivity (Fig.3(a)). While detailed information on existing PAWR platforms is not available, as shown in Fig. 3(b), we have designed NEXXT to include both unique research opportunities and complementary features to benefit the PAWR community. The unique research areas (THz, mmWave, MIRF UG) and large scale infrastructure deployment (40 sites, 400 miles) are blended with common features (e.g., SDN, GENI [40]) that will allow users to seamlessly benefit from all PAWR platforms.

## Section II Platform Technical Architecture Design

NEXTT will deploy an NG-RAN architecture [84, 96] leveraging existing private (Allo) and public (Lincoln, UNL) fiber, vertical, and mobile infrastructure (Fig. 4(a)). NEXTT will utilize an **X-haul Plane (XHP)** between central unit (CU) and distributed units (DUs) to facilitate user-configurable functional splits between CU-DUs. To support the diverse IoT use cases, NEXTT architecture includes **hybrid software defined distributed units (SD-DUs)** that provide a seamless continuum of **sub-6GHz-mmWave-underground wireless** connectivity. Through an integrated software architecture and an SDN-based backend, a **network slicing for multi-user experimentation** functionality will provide NEXTT the flexibility to function for the varied use-cases. Drawing an analogy between NEXTT users and virtual network operators, NEXTT will dynamically create and terminate virtual slices for users on-demand, while scheduling physical resources on the platform. Slices will be characterized by resource parameters such as computing and radio resource requirements, as well as Quality of Service (QoS) parameters such as average throughput and delay bounds. Within a slice, a user-preferred Radio Access Technology (RAT) can be deployed, along with custom traffic engineering solutions that are best suited to the use case. NEXTT infrastructure will leverage **SDN and NFV**, allowing for easy programmability, secure operation, and policy-based slicing capabilities for coexisting verticals [36, 80]. This architecture will serve as the underlying fabric that ties together a myriad of research opportunities across **mobile mmWave, THz**, and



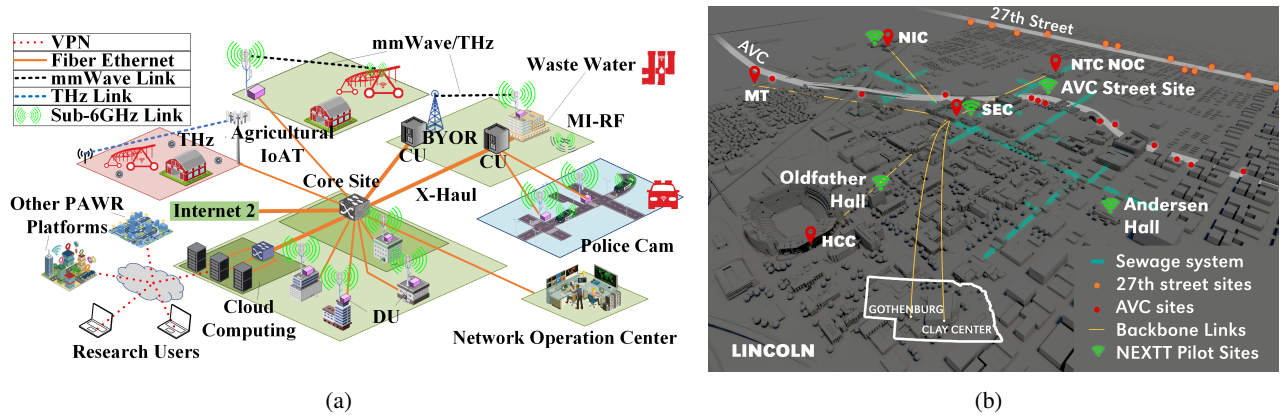


Figure 4: (a) NEXTT architecture and (b) sites (best viewed in color).

hybrid MRF underground communications, as well as dynamic spectrum sharing, while also serving as a live conduit for network slicing research.

To mitigate potential risks and establish a strong foundation for NEXTT, the team has deployed the **Ignite Lincoln NEXTT Pilot Testbed** over the last year with support from a US Ignite Smart Gigabit Communities (SGC) project and an NSF grant [84]. The Pilot Testbed includes three major components of the proposed NEXTT architecture (Fig. 4(a)): SD-DUs, fiber Ethernet-based X-haul network, and cloud-based baseband processing and data storage. SD-DUs are deployed on a small-cell site at a Lincoln traffic intersection and four sites on the UNL campus. In the following, we describe the proposed technical architecture design in detail along with existing capabilities as a part of NEXTT Pilot and local community resources.

## II.1 NEXTT Wireless Substrate

The wireless substrate will support police video streaming, underground infrastructure monitoring, and irrigation automation use cases, as well as high-density generic IoAT research through *four types of physical infrastructure sites*: (1) high-bandwidth traffic corridors, (2) wastewater manhole sites, (3) rural agricultural fields, and (4) publicly owned vertical infrastructure (building and tower sites), respectively (Fig. 4(b)). *The broad coverage area represented by these assets will allow NEXTT to provide users with varied real-world IoAT test environments, including rural, agricultural, industrial, and dense urban sites.* The wireless substrate will be constructed through three steps over Years 1-3 (see Section VI for detailed development plan). The three year deployment schedule will allow for flexible radio site selection based on research needs, partner commitments, and proximity to existing fiber assets.

(1) **Antelope Valley Corridor (AVC)**: AVC near UNL’s city campus has been selected for the police video streaming use case. Twelve traffic signal locations will feature high-end SD-DUs with mmWave capabilities and 20Gbps backbone links to create small cell sites. Site selection was based on proximity to Nebraska Innovation Campus (NIC), which hosts existing fiber connections and rack space for expansion (see Facilities). (2) **Wastewater Monitoring Sites**: NEXTT will partner with Lincoln Wastewater Systems (LWWS) and Teledyne to design wastewater flow monitoring systems and develop a flow monitoring application design in 12 wastewater manhole locations. Underground IoAT radios will be installed in enclosures near manholes (powered from nearby existing Lincoln sources and managed via consortium cellular modem and service) or in the upgraded traffic cabinets where power is readily available. (3) **Agricultural Sites**: Two rural agricultural sites will be leveraged to support the irrigation automation use case, Ag-IoAT research, and rural broadband connectivity research (Sect. II.3). These sites are UNL’s South Central Agriculture Lab (SCAL) near Clay Center, Nebraska (pop. 760), and Bayer’s Gothenburg Learning Center (GLC) near Gothenburg, Nebraska (pop. 3,574). (4) **Low-End IoAT Sites**: Twelve additional urban sites will be connected with 1 Gbps fiber links based on the existing fiber deployment in Lincoln. In addition, more than 100 remotely-manageable IoT devices will be integrated into AVC sites. These sites will be suitable for basic IoT research needs of our users.

In addition, most of the sites will support **Bring Your Own Radio (BYOR)** testing and experiments. More specifically, the Military Tower (MT) radio tower near AVC will provide a suitable location for radio testing.

Similarly, user IoAT radios can be integrated into more than 100 possible connections in AVC sites.

The **Pilot Testbed** currently includes five radio sites and two data sites across a Lincoln public street and UNL rooftops (Fig. 4(b)). SD-DUs are based on a high-end sub-6GHz 4x4 MIMO Software Defined Radio (SDR) transceiver. Four radio sites are on UNL rooftops: Oldfather Hall (OFH), Scott Engineering Center (SEC), Andersen Hall (AH), and Nebraska Innovation Campus (NIC). In addition, a small cell site is located along the AVC. The two data sites are the fiber hub at SEC and Holland Computing Center (HCC), which hosts Nebraska’s supercomputing infrastructure. The site planning provides a variety of channel conditions, and can support experiments such as direct links between multiple sites and between SD-DUs and mobile clients.

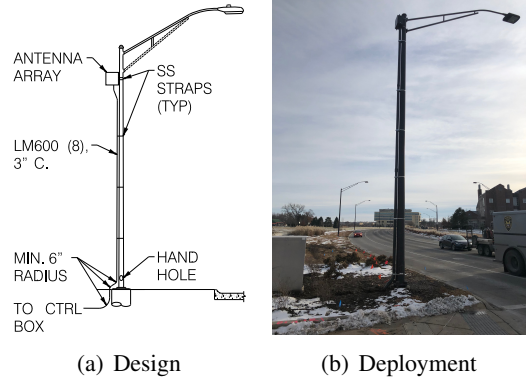


Figure 5: *Pilot AVC site (Credit: Olsson).*

For the design, deployment, site acquisition, and permits of the AVC site (Fig. 5), we worked with the Lincoln Mayor’s office, Lincoln’s Traffic Engineering Department, Olsson, Valmont, and the Commonwealth Electric Company. At the site, the antenna head is mounted near the top of a street light pole, and the transceiver is placed inside a weatherproof enclosure mounted adjacent to the nearby traffic cabinet, from which power and fiber network connections are obtained. Coaxial cables run in conduit up the pole to the antenna head. The AVC site provides **significant risk mitigation** for the proposed NEXTT architecture by establishing a proven site deployment workflow between local community members.

## II.2 NEXTT Infrastructure

NEXTT infrastructure will make use of dedicated high-speed fiber connectivity and shared network services from community partners, as well as a novel THz X-haul component. The infrastructure is based on four distinct components: (1) a dedicated fiber backbone containing a single hub and three distribution sites in Lincoln, (2) a dedicated fiber network that connects programmable radios installed at 12 traffic signal locations in Lincoln, (3) shared network service to connect IoAT devices at 12 traffic signal locations and underground IoAT devices at 12 wastewater monitoring sites, and (4) a rural network portion that connects to the Ag-IoAT installations at SCAL and GLC. Because all sites belong to partners (UNL, Lincoln, and Bayer) and are connected through dedicated fiber installations or shared network services, NEXTT infrastructure is flexible in terms of processing capacity, space allocation, utilization of existing right-of-way and occupancy permits for fiber infrastructure, and resource allocation based on user needs and experiment loads.

**(1) Backbone:** NEXTT will have *one core site*, UNL’s SEC, and *three distribution sites*, HCC, NIC, and MT, connected through a **100 Gbps backbone network** over dedicated fiber paths (Fig. 4(b)). HCC will meet NEXTT’s main offline processing needs and interface with users and schedule services and slices for experiments. NIC and MT will serve as CUs for the AVC sites with dedicated computation resources and support BYOR experiments, respectively. Finally, NTC will serve as NEXTT’s NOC and will be connected at 10 Gbps to the SEC hub site over a dedicated fiber path. **(2) AVC High-speed Fiber Network:** To support high traffic rates from the police camera streaming use case, we propose to deploy a high-performance fiber-optic network segment along the AVC. This high-speed corridor will connect 12 traffic signal sites to NIC CU using a dedicated fiber connection to each site provided by Lincoln. We will consider both a single-fiber 2-channel Dense Wavelength Division Multiplexing (DWDM) solution as well as a multiple fiber solution with 10Gbps bidirectional optics per fiber, depending on the availability of PAWR equipment. At each site, a hardened Ethernet switch will provide both X-haul and management access to the SD-DUs. More than 100 additional IoAT end devices can also be connected, resulting in a **dense urban IoAT testbed**. The 2x10 Gbps optical channels can carry the data to/from either the SD-DU or the IoAT devices or both, depending on the desired testbed configuration. **(3) Shared Urban Network Service:** We will use a shared network service for connecting the remaining urban SD-DU and IoAT locations to SEC. In particular, 12 small cell sites along 27th Street will be connected through Allo’s 1 Gbps VLAN service. In addition, the wastewater monitoring sites will be connected for out of band management

through either Allo VLAN service or a PAWR consortium wireless service, where possible. **(4) Rural Network Access for Ag-IoAT:** The Ag-IoAT sites are located in two rural communities. We propose to use a commercial 1 Gbps service through a local ISP (Windstream, LLC) for connectivity from SCAL to SEC. Data from SDT towers supporting advanced radios (such as SD-DU and THz) will be carried through the SDT backbone network. Wired network connectivity from Gothenburg to the SEC hub site will be through NebraskaLink.

**X-haul Plane (XHP):** XHP is the logical connection between SD-DUs and CUs, where data storage and processing may take place. Based on user requirements, XHP can act as one of the many potential functional splits, ranging from backhaul, carrying application layer data, to fronthaul, carrying digital baseband signals. **The Pilot Testbed** features a preliminary XHP implementation bridging five SD-DUs with HCC (Fig. 6). An aggregation switch located in SEC is connected to each SD-DU via two pairs of 10 Gbps Ethernet (GbE) dedicated fiber, and to HCC and Internet 2 via 100GbE connectivity. To facilitate baseband signal transportation in Common Public Radio Interface over Ethernet (eCPRI) [95] format, an FPGA server is placed at the aggregation switch to transcode eCPRI-formatted IQ data. Current implementation targets ‘User Plane over IP’ option of eCPRI and the remaining four methods of splitting will be implemented. The eCPRI protocol will also reside on the FPGA boards of SD-DUs by adding a pair of eCPRI encoders/decoders. The aggregation switch and the FPGA server can support a total of 100Gbps traffic from the five SD-DUs and will be scaled to support all SD-DUs.

**Baseband Processing and Data Storage:** NEXTT architecture supports baseband processing to be carried out in high performance computing (HPC) clusters at HCC [8], which will also provide user scheduling and short-term data storage services. HCC offers users two HPC clusters, a private cloud environment, and an access portal to the Open Science Grid (OSG) [13]. HCC resources are configured to allow direct access to the **Pilot Testbed**, where project related software tools, including UHD and GNURadio, are available.

### II.3 Ag-IoAT Sites

We will demonstrate the applicability of NEXTT’s NG-RAN wireless infrastructure in rural environments. To facilitate the design, implementation, and evaluation of *next-generation agricultural connectivity*, NEXTT will focus on two challenges: (1) connectivity *within* the field and (2) rural broadband connectivity *to* the field (Fig. 7(a)). NEXTT will provide sustainable access to high-quality agricultural research fields where wireless innovations can be evaluated with scientific rigor, unprecedented connectivity, scale, and bandwidth. NEXTT will deploy two small-cell instances in two prominent agricultural fields in Nebraska as described below.

**SCAL Site:** The primary site will be located at the Irmak Research Laboratory’s advanced agricultural engineering research infrastructures at SCAL. Remote access to the existing Ag-IoAT testbed at SCAL, operational for a decade [92], will be provided to researchers and rural communities to inform public decision-making. We will establish an NG-RAN architecture (Fig. 7(a)) that mirrors NEXTT urban architecture and *provides advanced connectivity in a set of large-scale agricultural fields*. SCAL will feature an SD-DU for an agricultural small cell on permanent structures, such as buildings and irrigation systems (e.g., Valmont center pivot systems). SD-DUs will serve *Underground Things (UTs)*, where a part of or the entire system resides underground and is sufficiently hardened for agricultural field use [99]. **Cloud services** will be used for data storage, real-time processing of field conditions, crop production and management-related decision-making, and integration with other databases (e.g., weather, soil). NEXTT will utilize cloud services in HCC and edge clouds at SCAL. In addition, LoRa experiments will be facilitated through the SDT LoRaWAN tower in Woodriver, Nebraska, which covers SCAL fields, and their backend connectivity.

**Bayer GLC Site:** A second small cell with similar capabilities will be established in Bayer’s Gothenberg research fields. GLC includes 320-acres of fields for research plots in multiple crops, high-performance

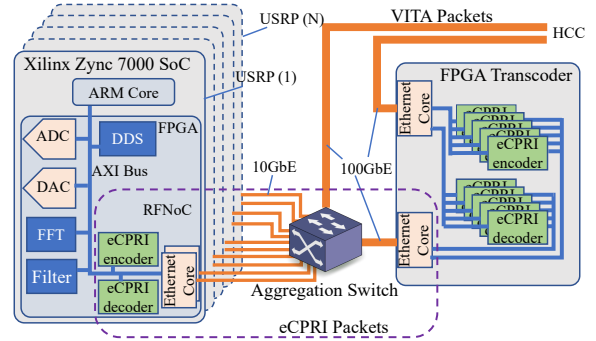


Figure 6: *X-Haul Plane Architecture.*



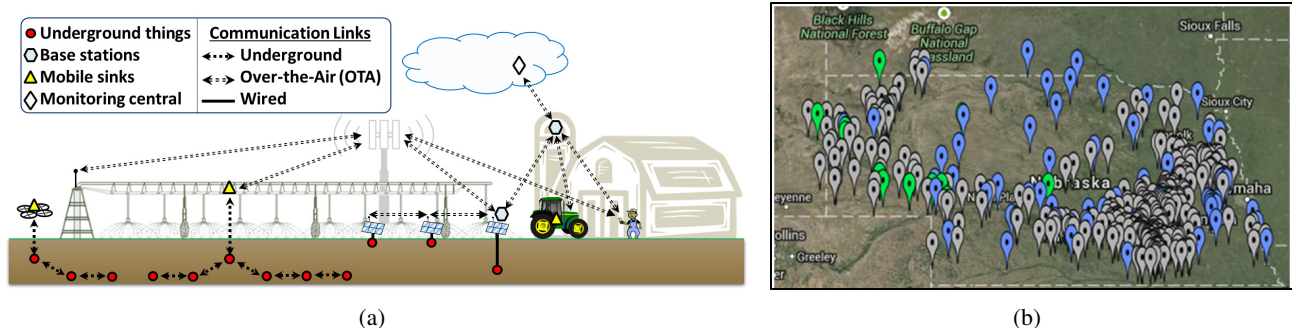


Figure 7: (a) *Ag-IoAT Site Architecture* and (b) *NAWMN cooperators/partners geographic locations in Nebraska*. broadband connectivity with an 80 by 160 ft automated rainout shelter. GLC farms focus on improving product performance and agronomic practices to preserve water resources and enhance yields under limited water conditions. NebraskaLink will identify fiber access from Lincoln to GLC, and the Small Data Tech LoRaWAN tower in Gothenburg, which covers GLC fields, will enable LoRa experiments. In addition to field support, Bayer’s Climate Corporation will support the development of the agricultural monitoring and automation use case through digital agriculture tools, including delivery of satellite imagery and weather data for the fields.

**THz X-Haul for Rural Broadband Connectivity:** Approximately 82% of the 116,000 active irrigation wells in Nebraska are located within 120 km of SCAL, which makes it one of the most heavily irrigated areas in the world. According to Valmont’s best estimates, only 30% of irrigation systems are *connected*, i.e., they utilize some type of remote monitoring and control (AgSense, FieldNet, FieldWise, ReinCloud, etc.). Lack of rural broadband connectivity, due to extreme costs of deploying fiber, is one of the main reasons for this low adoption rate. To this end, we will showcase the feasibility of THz X-haul links in the sites. THz X-haul links will consist of two nodes: (1) a THz DU collecting data from the users within its coverage range and (2) a gateway connected to the distribution site through a fiber optical link. Each node will incorporate a full THz transceiver with separate transmit/receive chains able to up/down-convert a digital intermediate frequency (IF) with up to 32 GHz bandwidth to/from 225 GHz, with demonstrated communication ranges of up to 2.1 km. The nodes will be mounted on custom-made poles to be jointly-designed with Valmont. The pole heights will be determined so to provide line-of-sight visibility between the nodes. In addition, we will support the testing of new THz transceivers and antennas brought by researchers and the use of the platform for long-range sensing applications.

Through these structures, THz, mmWave, and/or LoRa links will serve five automated weather stations deployed in nearby large-scale (160 acres each) fields to engage farmers. Weather variables (e.g., maximum and minimum air temperature, relative humidity, solar radiation, wind speed and direction, precipitation) will be transmitted to decision-makers to support effective farming practices. We will leverage the unique and large user-base of the Nebraska Agricultural Water Management Network (NAWMN) (Fig. 7(b)) to recruit growers to create new NEXTT sites and create a connected rural broadband connectivity testbed through THz X-haul links. In addition to this area, NEXTT sites can be established across Nebraska, following NAWMN’s succeed-educate-recruit model. In the long term, the long and variable distances between NEXTT sites will provide a unique large-scale experimentation platform for partners (e.g., Valmont, SDT, Bayer, IntelliFarm, Solvz) with interests on LoRa, agricultural connectivity, and rural broadband.

## II.4 NEXTT Software Architecture

NEXTT’s software components will be developed by software engineers at DPL in collaboration with RENCI for ExoGENI integration. Following DPL’s design principles, NEXTT software architecture will have a strict layered architecture (Fig. 8). 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 NEXTT will contain the Authentication system leveraging CILogon [39] and InCommon [46]. The second layer of NEXTT will include the actual front end as defined in Section V. The third layer will include ORCA [41], which will serve as the gatekeeper to all the resources of ExoGENI, HCC and the matrix of Radios. The user facing front end will be a cloud hosted web portal that orchestrates the various aspects of NEXTT. The mission of the Researcher Portal is to obfuscate 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 NEXTT. The Administrator Portal will allow for administration of NEXTT. At the ORCA layer, the most notable HCC resources are shown in Fig. 8. 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 Super Computers are available to provide either real-time or post experiment analysis. Radios will include at mini which is required to support the wireless breakthrough use cases of

Realizing the NEXTT vision through an advanced network architecture (Fig. 4(a)) relies on **contributions from community partners**. The diversity of these contributions are illustrated in Fig. 9 by the different colors and with existing committed resources (solid lines) and planned expansions (dotted lines) through the PAWR project. These contributions are listed in Table 1.

### Section III Description of Research Community Support and New Research to be Uniquely Enabled by the Platform

More than 35 academic researchers, with more than \$38M in active NSF funding, are committed to using NEXTT (see letters of support). NEXTT will support targeted wireless breakthroughs and user research interests through its NG-RAN architecture, which allows network-wide, vertical-specific, and/or site-specific research

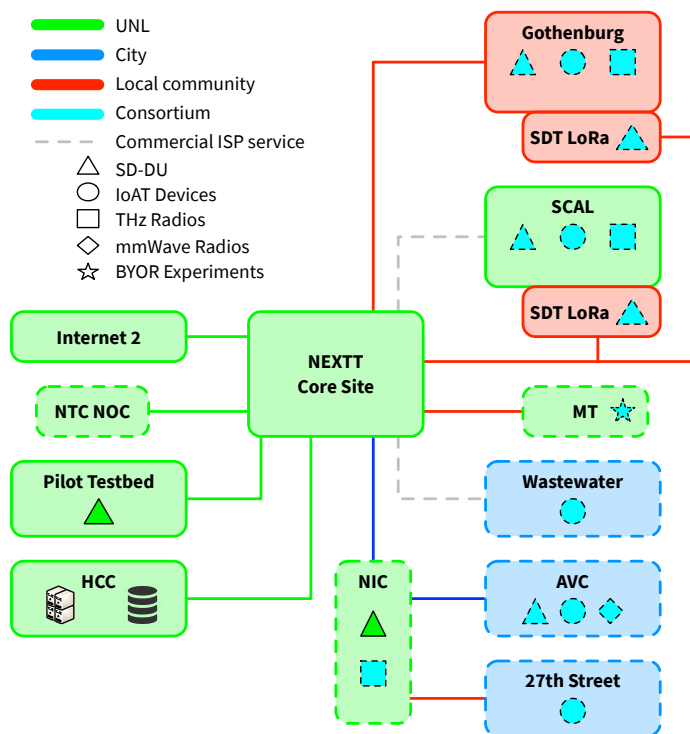


Figure 9: *Community contributions in NEXTT Architecture.*

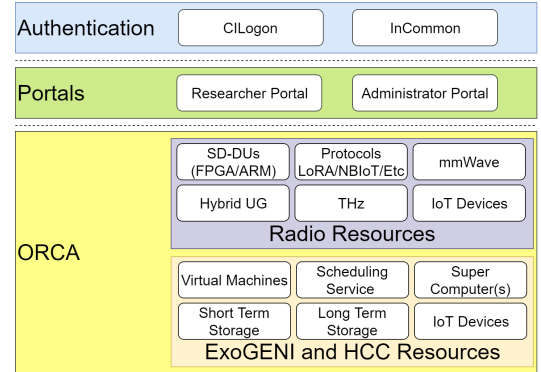


Figure 8: *Static Architecture Diagram (Credit: DPL).*

| <b>Institution</b> | <b>Contribution</b>                             |
|--------------------|-------------------------------------------------|
| City of Lincoln    | Dedicated urban fiber                           |
|                    | Traffic light small-cell sites                  |
|                    | Wastewater manhole sites                        |
| UNL                | Dedicated fiber network                         |
|                    | Super computing facilities                      |
|                    | Internet 2 connectivity                         |
|                    | Agricultural fields, Clay Center, NE            |
|                    | Network Operating Center (NOC)                  |
| Allo               | VLAN service over shared fiber                  |
| Bayer              | Agricultural fields, Gothenburg, NE             |
| Valmont            | In-kind pole & design, irrigation system access |
| SDT                | Rural LoRa towers and backbone access           |
| NebraskaLink       | Rural fiber network                             |
| RENCI              | ExoGENI expertise                               |
| DPL                | Software development resources                  |

Table 1: *NEXTT Community Contributions.*

support. NEXTT focuses on: **(1) DSS NG-RAN** network architecture for flexible research and experimentation, **(2) mobile mmWave communications** for real-time video streaming, **(3) long-range, high-rate MIRF hybrid wireless underground communication**, and **(4) long-range ultra-broadband THz communication** for wireless X-haul and long-range sensing applications. NEXTT will provide a *hybrid wireless continuum* via *underground and over-the-air* and *urban and rural* use cases.

### III.1 Secure Dynamic Spectrum Sharing via NG-RAN

The NG-RAN design will follow a cloud-native approach centered around a micro-services architecture. The use of DevOps (continuous deployment and integration) will enable deployment automation and management, automated function onboarding, performance testing, and scaling, further enhancing NEXTT’s reproducibility and programmability. In addition, as part of NG-RAN, NEXTT will create standards for researchers to design and deploy their own network functions, and via open interface access to XHP configuration and data, researchers can configure a vertical-specific architecture. Supporting this goal, users can also collect comprehensive spectrum, radio, and network information to advanced dynamic spectrum sharing (DSS) solutions, that are needed for IoAT applications in highly dense deployments. *Coupling X-haul plane with spectrum sensing within the NEXTT architecture* has the potential to provide new capabilities for DSS. For example, in our recent NSF project, we are transforming these approaches by leveraging the coordinated multi point (CoMP) communication structure for sensing, and developing a CoMP-assisted spectrum sensing approaches. To this end, NEXTT architecture will facilitate evaluation of novel cloud-assisted spectrum sensing solutions and their sensing accuracy with minimum resource utilization. NEXTT will enable novel wireless network security research. XHP allows researchers to configure the experimental architecture and collect information about the spectrum utilization of a wide variety of IoAT applications. It opens a new horizon for experimental wireless security research. With a large span of the IoAT network testbed covering public safety, infrastructure, and smart agriculture, the researchers are well equipped to evaluate the possibility of malicious cyber-attacks towards these critical infrastructures and the robustness of existing countermeasures across a city-scale large network. Finally, a **NEXTT RF database** for reproducible experimentation similar to a few other fields (e.g., ImageNET [44]) will be created with XHP. NEXTT will support research in policy-based optimal functional split, IoAT standardization (LoRa, Sigfox, and NB-IoT), phase/time synchronization, spectrum sharing for IoAT, cyber-physical systems, radio/CPRI over Ethernet, neural networks for IoAT communication, software-defined networking, mobile edge cloud, and cyber threat defense. In this manner, NEXTT will create a closed feedback loop wherein the outcome of experiments performed on the testbed will serve to improve the platform implementation.

### III.2 Mobile mmWave Communications

mmWave technology has been strategically selected as a core NEXTT platform to serve a wide range of current industry and academic partners and future users. While mmWave technology has been envisioned to drive 5G+ wireless systems, currently, mmWave testbeds are not widely accessible to researchers and developers. Further, existing mmWave communication systems are confined to stationary end point scenarios due to **(1)** difficulties in real-time adaptation to changes in the propagation environment, **(2)** high temporal overhead while tracking mobile users, and **(3)** high energy overhead associated with link maintenance and mobility management. The NEXTT design, based on commercially available phased array antennas, SDR platforms, and frequency converters, will establish a platform that appeals to researchers working on a wide range of topics, from physical layer design to communication protocols and application development. Design highlights include *high energy efficiency*, *real-time adaptivity*, and *high mobility support* for a mmWave system, which are the foundational requirements of 5G+ systems. NEXTT will allow access to vertical applications through its API and provide services to various academic, industry, and community applications of interest. The NEXTT testbed design is based on insights gained in our prior work on channel estimation [71], beam discovery and tracking [90], and user scheduling and mobility management [73] in mmWave systems.

Based on our conceptual studies and associated field measurements, we have demonstrated that mobile mmWave communication with large arrays involve situations in which angular bins vary at time scales, comparable to the coherence times of the channels. Therefore, small target location changes may lead to

big changes in subarray (and switch) configurations. This eliminates the use of classical direction sweeping, multi-band direction estimation, in moderate to high-mobility settings under mmWave. To address this issue, we will build on our hybrid receiver architecture (Fig. 10) and associated physical-layer techniques to support mobile multiuser communication. Our receiver architecture consists of the phase shifter, followed by a switch that chooses appropriate configurations for the combinations of  $n_r$  antenna elements processed at subsequent  $m$  RF chains. In contrast to existing techniques, our architecture can handle beam tracking by slowly varying antenna gains and the switch configuration can remain unchanged for extended durations.

Note that capacity achieving configurations for our setup in Fig. 10 results in a non-convex combinatorial optimization problem. In contrast, our platform poses the optimal beamforming problem as an instance of switch scheduling, thereby enabling polynomial-time solutions with a provably small performance gap to the capacity. Accordingly, users will be able to find the sequence of extreme points and evaluate the coefficients to find the exact time share between configurations.

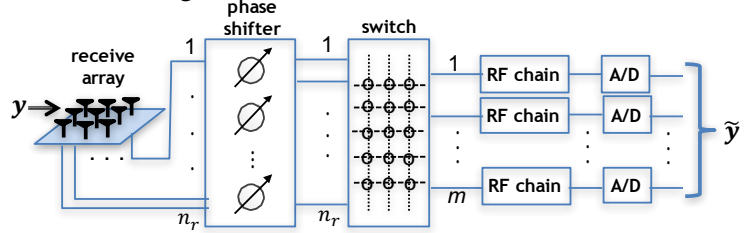


Figure 10: *Receiver architecture illustrating phase shifters at the output of each antenna element, followed by an  $n_r \times m$  switch for the subsequent RF chains.*

To highlight the capabilities of our mmWave system design, in collaboration with WatchGuard, a video source (Fig. 2(a)) will be mounted on a vehicle, which will stream video to a base station connected to the fiber backbone. Our core partner, LPD, has an immediate need for such a system, and will be the first and immediate beneficiary. NEXTT is designed to handle large volumes of real-time data thanks to phased-array antennas and will also be capable of handling the high mobility of the source platform. The mmWave system will be available for direct use and testing for a wide range of application scenarios. Mobile terminals will be mounted on LPD vehicles where tests and validations can be performed at virtually any speed range. Tests in AVC will be performed without high reconfiguration overhead. Some of the additional target test applications include (1) EMS and first responder scenarios, (2) low (pedestrian) speed urban tests, (3) smart agriculture scenarios involving multiple autonomously operating farming equipment and vehicles, and (4) wireless backbones for wireless communities.

The NEXTT mmWave platform is designed to appeal to researchers working on a wide range of topics, from physical layer design to communication protocols and application development. The extremely flexible, state-of-the-art phased-array antenna system lends itself to implementation and testing of a wide variety of physical layer algorithms. The SDR-based design also allows for the implementation of resource management, scheduling, mobility management, and other algorithms without the need for hardware reconfiguration. This is especially appealing for academic institutions and corporations, which may not have access to mmWave hardware platforms. With the contributions of our partners and users, we will build a publicly accessible mmWave solution library. Moreover, in later stages, NEXTT users will be able to replace and test hardware components, with minimal constraints on compatibility with the existing design. We note that our proposed testbed will primarily focus on technologies and solutions necessary to enable highly mobile systems, complementing and advancing ongoing efforts under COSMOS. Our partnership with LPD and WatchGuard will allow NEXTT researchers to implement and test real use cases that require high bandwidth and real-time data connectivity, and present our community partners and users with a tested and reliable basis for mobile mmWave development and testing.

### III.3 THz X-Haul

Going a step beyond mmWaves, THz-band (0.1–10 THz) communication is envisioned as a potential key wireless technology to satisfy the need for significantly higher wireless data rates [47, 94, 31, 72]. The THz frequency band, which lies in between mmWaves and the far infrared, is one of the least explored regions in the EM spectrum. For many decades, the lack of compact high-power transmitters and high-sensitivity receivers able to work at room temperature has hampered the use of the THz band for any application beyond sensing. However, recent advancements with several device technologies are closing the THz gap, by means of new electronic [82, 26, 43, 74, 97, 78], photonic [93, 59, 81, 76] and plasmonic [83, 49, 67, 29, 69, 28, 34, 30] approaches.

Independently of the specific enabling technology, THz-band communications bring many new opportunities to the wireless community. The very large available bandwidth at THz-band (several hundreds of GHz) frequencies will alleviate the spectrum scarcity problems and capacity limitations of current wireless networks, and enable new applications in the consumer, industrial, medical, and military fields. Nevertheless, the major challenge at THz-band frequencies is the limited communication distance, which results from the very high channel path-loss and the limited transmission power of mm-wave and THz transceivers. This requires the development of new device technologies, channel models and tailored physical and link layer solutions to enable practical long-range THz communications.

During the last decade, and with the support of the NSF (Awards CCF-1349828 and ECCS-1608579), we have established the theoretical foundations of THz communications, by designing and developing analytical models of innovative THz transceivers [69, 28] and antennas [64, 67, 29], THz-band channel models [65, 54, 58], and new physical layer solutions (including modulation [68, 52], coding [66, 27], synchronization [51, 53] and ultra-massive MIMO communications [34, 30]) to support ultra-broadband THz links.

In addition, for the last two years, we have been working on the development of the TeraNova testbed at UB, i.e., the first integrated testbed in the world for ultra-broadband wireless communications at *true* THz frequencies (i.e., above 1 THz), with the support of the NSF CISE Research Infrastructure (CRI) program (Award #1730148). More recently, aimed at increasing the communication distance at THz frequencies, we have started a fruitful collaboration with NASA JPL's (Dr. Jose V. Siles) Sub-millimeter Wave Advanced Technologies (SWAT) Group. SWAT currently has the highest power THz sources, with world-record output power in excess of 100 mW at 225 GHz, which can be further increased through power combining. By integrating the TeraNova testbed with the NASA JPL technology (Fig. 11), we have recently demonstrated multi-km multi-Gbps transmissions. We will leverage this research and establish fixed multi-km THz wireless backhaul links that will support aggregated traffic with multi-Gbps rates to provide our community early access to this exciting technology.

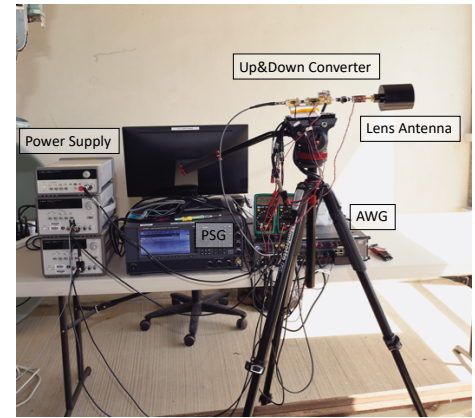


Figure 11: *Demoed THz experimental setup.*

The THz X-Haul will enable transformative research across different areas. First, it will enable the study of the impact of different atmospheric and weather phenomena on the propagation of THz waves. Extensive data sets can be used to validate new deterministic and stochastic channel models and to derive empirical models. In addition, new channel estimation and equalization techniques suitable for ultra-broadband channels can be developed and tested. Correlation between weather forecast and channel properties can be studied and used for the development of machine-learning based dynamic channel estimation and equalization algorithms.

At the physical layer, THz sites will enable the testing of different time, frequency, and phase synchronization schemes with real THz devices and over long distances. In relation to the distance, ways to increase the communication distance will be explored through partnership with Valmont in the research and development of smart THz-connected pivots [32]. NEXTT will support the testing of new antenna array architectures and novel ultra-massive MIMO communication schemes [34]. In addition, mechanisms to efficiently multiplex multiple users or data-streams over the THz X-Haul, including the possibility to leverage multiple absorption-defined transmission windows and space-time-frequency modulations, will be explored.

Moreover, given the abundant resources in available frequency spectrum, high degrees of freedom in large-scale antenna arrays within small form factors and multipath-rich channel environments, the THz X-Haul can optimize resource allocation in multiple dimensions to achieve Tbps throughput. Finally, NEXXT will support the integration and testing of new high-power transceivers and directional antennas for THz communications. These include, among others, new multi-band transceivers and antennas able to synergistically exploit RF, mmWave and THz bands for dynamic spectrum communications [33]. NEXXT will also support THz sensing and imaging and applications, including for example long-range sensing of atmospheric conditions and bio-chemical elements and study of their correlation with the evolution of the fields.



### III.4 High Data Rate, Long Range, Hybrid Wireless Underground Communication

Going from above ground to under, NEXTT will facilitate the evaluation of disruptive wireless underground communication technologies for unique IoAT use cases, such as urban underground infrastructure monitoring and agricultural soil monitoring. Existing OTA wireless communication solutions face significant challenges in meeting the unique requirements of Ag-IoAT applications. Integration of UG communications with Ag-IoAT will help conserve water resources and improve crop yields [99]; advances in Ag-IoAT will benefit underground infrastructure and landslide monitoring, pipeline assessment, underground mining, and border patrol applications [35, 45, 85, 87, 88, 89, 98].

UG communication solutions are in their infancy and depend on off-the-shelf radios, which are not designed for the medium. For example, current maximum attainable communication ranges for underground-to-underground links are limited to a few meters, which prohibits the establishment of *multi-hop* underground networks. On the other hand, UG radios can establish communication with aboveground devices at distances over 150m. While promising, these distances are still limited for some applications, e.g., agricultural automation where large fields need monitoring with a limited network architecture [45]. In addition, the data rates attained by commercial off-the-shelf (COTS) solutions are limited to tens of kbps, which prohibits data-hungry applications, such as real-time monitoring and imaging of underground pipes.

To enhance wireless UG communication ranges, supported by our NSF projects (CAREER-0953900, DBI-1331895, CNS-1619285), we have devised a novel UG beamforming solution using adaptive antenna arrays to improve wireless underground communications performance [86]. Our soil moisture adaptive beamforming (SMABF) algorithm with a novel UG planar antenna array result in significant range improvements. Similarly, we have shown that multi-carrier underground communication through soil-adaptive subcarrier and system bandwidth operation can significantly improve data rates [88, 85]. Yet, practical *and large-scale* evaluations of these techniques are cost prohibitive, limiting rapid commercialization for practical applications. NEXTT will feature the practical implementations of long-range, high-data-rate wireless underground communication solutions in two unique verticals. First, our current field-hardened implementation of TI cc430-based wireless UG radio with our patented antenna design, *Irrrometer* soil moisture sensors, and aboveground access for on-site programming will be retrofitted with an embedded SDR (e.g., Ettus E310) and OTA cellular connectivity for remote access and programmability of our existing field deployment at SCAL. Second, deployment of our multi-carrier UG communication algorithm will be implemented on SDRs that acquire real-time soil moisture sensor information and adapt the system and subcarrier bandwidth in run time, making this approach another candidate for 5G flexible numerology applications. Third, our high-density UG planar antenna array will be integrated for SMABF algorithm deployment and virtual antenna array operation for long-range UG connectivity. Higher permittivity of soil, compared to air, leads to much smaller wavelengths for a particular operation frequency. Therefore, compact antenna arrays can be used for UG communication at sub-GHz frequencies. This enhanced UG RF system will allow research in adaptive beamforming, UG multi-carrier communications, subcarrier adaptation algorithms, protocol development, UG network design, and wireless communication research in challenging environments.

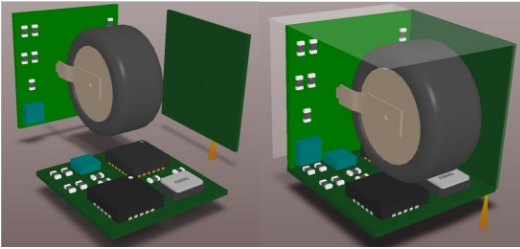


Figure 12: *3D conceptual design of the hybrid MIRF radio with integrated circuitry, antennas, and energy source.*

Finally, we will progressively integrate our evolving RF UG platform with GT's MI UG platform for hybrid MIRF UG platforms. In particular, at GT, we have already implemented a pure MI-based transceiver with an energy harvesting unit, an ultra-low power MCU MSP430G2553, and a MI-based transceiver; and successfully demonstrated MI communications between devices [77]. The hybrid MIRF UG platform will be equipped with both MI/RF transceivers, multitasking sensing components with Teledyne and Irrrometer sensors, and activated through optimized software modules that can be remotely programmed (Fig. 12). Specifically, our MI antenna radiates a directional magnetic beam that creates *underground* sub-networks with linear topology while RF allows the

| Research Area                    | User                                          |             |                                                 |             |
|----------------------------------|-----------------------------------------------|-------------|-------------------------------------------------|-------------|
|                                  | Name                                          | Affiliation | Name                                            | Affiliation |
| IoT                              | Thomas Hou                                    | VT          | Ming-Chun Huang                                 | CWRU        |
|                                  | Jung-Min (Jerry) Park                         | VT          | Walid Saad                                      | VT          |
|                                  | Sajal Das                                     | MST         | Maciej Zawodniok                                | MST         |
|                                  | Tarek Abdelzaher                              | UIUC        | <i>Lincoln Electric System</i> [10]             |             |
| Agricultural and Underground IoT | Zhi Sun                                       | UB          | Abdul Salam                                     | Purdue      |
|                                  | Prakash Ranganathan                           | UND         | Santosh Pitla                                   | UNL         |
|                                  | <i>AER Inc.</i> [1]                           |             | <i>CropMetrics</i> [5]                          |             |
|                                  | <i>Garner Industries</i> [7]                  |             | <i>IRROMETER</i> [9]                            |             |
|                                  | <i>Quantified Ag</i> [14]                     |             | <i>RealmFive</i> [15]                           |             |
|                                  | <i>Teledyne</i> [19]                          |             | <i>Bayer Crop Science</i> [2]                   |             |
|                                  | <i>SmallData Tech</i> [17]                    |             | <i>Valmont Industries</i> [23]                  |             |
| 5G & mmWave                      | Zhu Han                                       | UH          | Dario Pompili                                   | Rutgers     |
|                                  | Raghuraman Mudumbai                           | UIowa       | Soura Dasgupta                                  | UIowa       |
|                                  | Violet Syrotiuk                               | ASU         | Chandra Murthy                                  | IISC        |
|                                  | Rajesh Sundaresan                             | IISC        | Baek-Young Choi                                 | UMKC        |
|                                  | <i>EKINOPS</i> [6]                            |             | <i>SmartWAVE</i> [18]                           |             |
|                                  | <i>Ruckus Wireless</i> [16]                   |             | <i>Unite Private Networks</i> [22]              |             |
|                                  | <i>Bluestem Network</i> [3]                   |             |                                                 |             |
| THz                              | Richard Ridgway                               | OSU         | Dimitrios Koutsonikolas                         | UB          |
|                                  | Danijela Cabric                               | UCLA        | <i>NASA JPL</i> [11]                            |             |
| Video Streaming                  | Rui (April) Dai                               | Cincinnati  | Feng Qian                                       | UMN         |
|                                  | <i>WatchGuard Video</i> [24]                  |             |                                                 |             |
| Security                         | Kemal Akkaya                                  | FIU         | A. Selcuk Uluagac                               | FIU         |
|                                  | Wenjia Li                                     | NYIT        | Koushik Sinha                                   | SIU         |
| Dynamic Spectrum Sharing         | Jiang (Linda) Xie                             | UNCC        | Kai Zeng                                        | GMU         |
| Cloud/Fog computing              | Prasad Calyam                                 | Missouri    | Vijay Sivaraman                                 | UNSW        |
|                                  | Ilya Baldin                                   | RENCI       |                                                 |             |
| Transportation                   | Christian Poellebauer                         | ND          | Abdallah Khreishah                              | NJIT        |
|                                  | Giorgio Rizzoni                               | OSU         | Min Song                                        | SIT         |
|                                  | <i>Toyota InfoTechnology Center Inc.</i> [20] |             | <i>Transportation Research Center Inc.</i> [21] |             |
| Digital Law                      | Justin (Gus) Hurwitz                          | UNL         |                                                 |             |

Table 2: *Academic and industry (italic) users and research areas enabled by NEXTT.*

interconnection between sub-networks and OTA devices. The dual topology will allow research in improving energy efficiency, UG network architecture; and cross-layer protocol development for hybrid MI/RF operations.

NEXTT will support two IoAT applications that will be uniquely enabled by transformative research in wireless UG communications: *city wastewater monitoring* and *agricultural soil moisture monitoring*, in collaboration with our community partners LWWS, Teledyne, Valmont, Irrometer, and Bayer (see letters of support). These applications will provide a diverse set of UG communication requirements and realistic scenarios to implement and test the range- and capacity-enhancing solutions in large scales. This work will address the UG communication problems for these applications and provide benchmarks for various classes of applications that require UG communications. We also envision that NEXTT wireless UG capabilities will facilitate development of underground versions of existing standards such as UG-LoRA and UG-Sigfox. We will design guidelines for NEXTT academic and industry communities to tailor the project solutions to their applications.

### III.5 Research Areas Enabled and Committed Users

As shown in Table 2, NEXTT will enable the research activities of **over 35 academic community members** across U.S. in these areas, with a total of \$38M NSF investments from CISE (CNS, OAC, IIS), ENG (ECCS, CMMI), SBE (SES), and MPS (AST) directorates; and **20 industry users**.

## Section IV Description of Engagement among Academic Researchers, Industry, and the Local Community

NEXTT, with support from over 80 academic, industry, and community members (see letters of support), will enable a diverse set of research interests (Section III). With a **strong Midwest concentration** of users and a large footprint across the U.S. (Fig. 13), NEXTT will support diverse research interests in urban *and* rural environments. **Community support for NEXTT starts at the top. Lincoln's mayor and UNL's chancellor are fully committed to NEXTT's deployment, with support from Senator Fischer and Governor Ricketts.**

**Urban Community:** UNL and Lincoln have partnered on more than \$800M in major infrastructure initiatives since 2012. One such partnership is the Lincoln Technology Improvement System (LTIS), a \$220M citywide broadband infrastructure project. Key to NEXTT's competitiveness on the national stage, LTIS is a 400+ mile long public/private broadband infrastructure based on a coalition building approach between public and private partners. NEXTT will leverage LTIS infrastructure to create a dense urban IoAT wireless testbed that will be deployed in

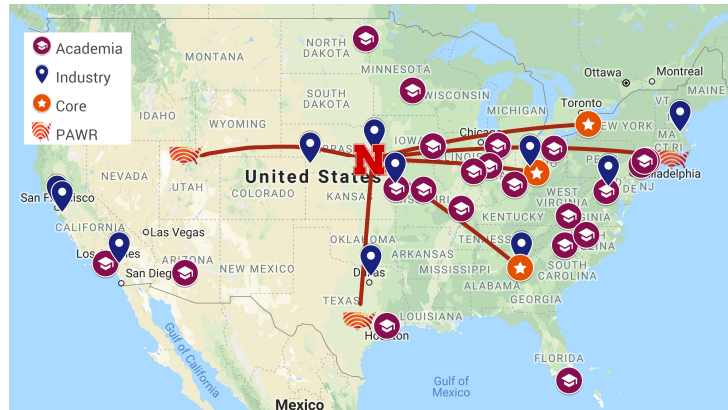


Figure 13: *NEXTT Community.*

conjunction with three Lincoln technology initiatives: LTIS Broadband, LTIS Small Cells, and Green Light Lincoln (GL2). LTIS Broadband will complete deployment of Fiber-to-the-Home infrastructure providing service availability to every home and business by summer 2019, and connect 150 public buildings, 75 non-profit entities, and 430 traffic signals by 2020. LTIS Small Cells is in the process of deploying 100+ advanced wireless smart street light poles around Lincoln. Equipment space, fiber, and power will be provided to NEXTT based on LTIS resources. GL2, an advanced traffic management initiative, will leverage the LTIS broadband infrastructure to upgrade connections, controllers, and software in more than 400 Lincoln traffic signal cabinets. GL2 will provide NEXTT additional fiber infrastructure, power, and equipment space in the traffic signal cabinets. NEXTT will be further supported by the Ignite Lincoln Smart Gigabit Communities (SGC) project, a gigabit applications development infrastructure and ecosystem deployed in partnership between Lincoln, UNL, and Allo. Allo is a leading provider of high-speed Internet service over fiber in Lincoln and a NEXTT partner. NEXTT community members will benefit from five years of successful LTIS broadband deployment. The NEXTT/LTIS partnership will enable fast and flexible deployment of multiple radio/antenna types connected with 1 Gbps, 10 Gbps, and 100 Gbps existing fiber-based connections. NEXTT will be accessible nationally to researchers via UNL's Internet 2 connectivity.

Community users for NEXTT's urban component include: Allo; WatchGuard; Teledyne; Lincoln's LPD, Partnership for Economic Development, Public Works Department, and Electric System; the Nebraska Department of Transportation; and Next Century Cities. Of particular interest is NEXTT's enhanced capabilities for law enforcement through technological breakthroughs. NEXTT's mobile mmWave system will enable real-time streaming and low-delay offloading of body and dashboard camera content. This is possible through the unique collaboration of academia (OSU, UNL), the local community (LPD), and industry (WatchGuard). WatchGuard will provide camera hardware and technical expertise, to be deployed on LPD-allowed platforms, where streaming video will be delivered using mmWave technology developed by academic partners. With this three-pronged approach, we will demonstrate how overcoming technological barriers lead to superior law enforcement capabilities and help strengthen public trust through transparency and accuracy.

One of the most challenging problems for cities is the management and maintenance of aging infrastructure. The challenge: How to deploy cost-effective, real-time sensor technology in underground infrastructure? The deployment of current sensor technology is cost prohibitive due largely to the cost of constructing physical connections for communications and power to the sensor. NEXTT, in partnership with LWWS and Teledyne,

will leverage the MIRF UG technologies to develop low cost, low power wireless sensors for stormwater and wastewater infrastructure.

**Rural Community:** Eighty percent of the 24 million American households that do not have reliable, affordable high-speed internet live in rural areas according to Federal Communications Commission (FCC). Moreover, Nebraska ranks first in the U.S. in irrigated acres and is home to many irrigation-related technologies (center-pivot irrigation and the emerging Agricultural IoATs). NEXTT will address the unique needs of the Midwest and other rural regions, which will benefit from advanced rural connectivity, by fostering economic growth. NEXTT's rural testbed capabilities are being deployed via the existing NAWMN platform [63, 60], which with 800 technology implementation platforms covering 800,000 hectares of irrigated land, is the largest irrigation, crop production, and water management network in the U.S. The combination of LTIS, GL2, and NAWMN will result in the largest, most diverse and advanced wireless experimentation platform available.

Wireless communication research in agricultural fields is challenging because of limited opportunities for the research community to access state-of-the-art agricultural operations. To realize the novel agriculture use case at SCAL, an existing state-of-the-art irrigation system equipped with variable rate irrigation and fertigation features will be utilized. This advanced system is the first such pivot in Nebraska. Our existing Ag-IoAT experimental field (16.5 ha), where the system deployed is divided into 40 equal size pie-shaped plots, allows precisely controlled applications in parallel based on different percentages of irrigation treatments and supports irrigation and fertilizer automation application [62, 61]. SCAL's advanced agricultural treatment capabilities and fiber connection to UNL will result in a next-generation wireless playground for agricultural partners to facilitate development of 5G agricultural wireless solutions. PI Irmak's unique research infrastructures are regarded as premier by the scientific community. These infrastructures, coupled with 5G technology, will enable us to implement advanced data gathering and their integration into real-world problem solving in autonomous center pivot irrigation applications and enable us to apply this innovative platform in subsurface drip irrigation, gravity irrigation, and low pressure irrigation applications; evapotranspiration measurements; plant physiology and phenology measurements; and other applications to develop next generation crop production systems.

NEXTT partners with a very unique and strong set of rural community members, including Bayer, Valmont, NebraskaLink, and SDT. Bayer will provide access to their fields in GLC for a NEXTT Ag-IoT site deployment, and their subsidiary Climate Corporation will provide expertise in use case development. GLC site will be connected to NEXTT core network through NebraskaLink in cooperation with PinPoint Communications. SDT's rural LoRa network covers primarily Nebraska and western Kansas (Fig. 14). SDT will provide NEXTT with backhaul and remote management for LoRaWAN based devices

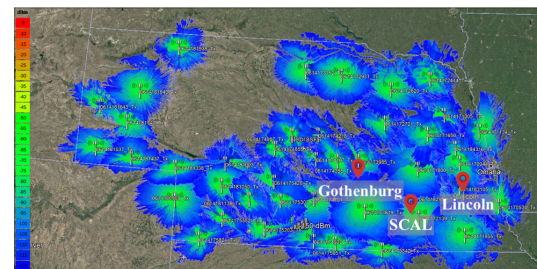


Figure 14: *SDT 2019 Nebraska LoRa Coverage* (Credit: SDT).

and remote sub-surface soil moisture installations, as well as a platform to conduct THz radio field testing, primarily through two towers that cover Bayer's GLC and UNL's SCAL. Both Valmont's Irrigation and its Engineered Support Structures divisions provide strong commitment to NEXTT by providing agricultural expertise in automated irrigation use case and engineering expertise to design and donate two structural poles for THz radio deployment. **Without such a strong industry commitment, deployment of a rural experimental platform is not possible.**

Additional partners interested in using the platform include Quantified Ag, CropMetrics, Irrrometer, Teledyne, RealmFive, SmartWAVE, and Garner. More than 35 academic researchers are committed to using NEXTT from institutions like UCLA, Virginia Tech, Purdue, Rutgers University, Florida International, Arizona State, Notre Dame, Univ. of Houston, and Univ. of Minnesota (i.e., more than \$38M in NSF funding). NEXTT also will inform community education. Lincoln Public Schools has a robust K-12 computer science (CS) curriculum, and was selected as the best K-12 CS education district in the U.S. in 2018 CS education week. The Lincoln Chamber of Commerce provides a bridge between education and industry via programs to help start-ups grow ventures. CodeLNK organizes computer science activities in the community, including cyber competitions and hackathons. DPL, as the core software development partner of NEXTT, will provide professional-grade software



for the unique needs of NEXTT community of users and the federated PAWR testbeds.

## Section V Alignment with the PAWR Vision

The NEXTT platform shares the PAWR goals of diversity, reproducibility of experimental results, broad usability, interoperability with other platforms, programmability, and open access as explained below.

**Diversity:** NEXTT’s novel heterogeneous architecture with hybrid components will support a ***diverse range of use cases, research topics, and wireless technologies***, including urban and rural verticals, cloud-based 5G, mmWave, THz, and hybrid wireless underground. NEXTT elevates back/mid/front-haul utility from a data interconnect to an experimental architecture component with the X-haul Plane concept, providing an essential tool for NG-RAN research and network slicing for multi-user experimentation. Research in policy-based optimal functional split, IoAT standardization (e.g., LoRa, Sigfox, and NB-IoT), phase/time synchronization, and DSS for IoAT will be enabled by NEXTT’s technology diversity. As discussed in Section III, NEXTT enables an array of research in cyber-physical systems, radio/CPRI over Ethernet, neural networks for IoAT communication and analytics, software-defined networking, mobile edge cloud, and cyber threat defense.

Energy-efficient mmWave devices based on hybrid beamforming will support real-time, high data-rate communication. The platform combines beam agility for highly directional communication in mobile environments with ultra-low-power characteristics for urban and rural applications. Hybrid wireless underground MIRC communication technologies will be unified within a hybrid, remotely accessible platform to enable novel rural soil moisture and underground infrastructure monitoring and support research in wireless communication in challenging environments. THz X-Haul links will provide fiber-optical-like backhaul connectivity to remote areas with minimal installation costs to allow users to evaluate performance of different THz communication strategies in real scenarios (e.g., changing weather conditions and traffic patterns).

**Reproducibility of Research:** NEXTT will provide extensive reproducibility capabilities in both urban and rural settings by leveraging an architecture based on the Pacific Research Platform for Experiment Data Storage and Retrieval. HCC is utilizing aspects of this architecture for large data set transfers for OSG and U.S. CMS, and has incorporated a high-bandwidth Flash I/O Network Appliance (FIONA) transfer node into its infrastructure. Utilizing this architecture and our unique XHP, the **NEXTT RF database** will store and replay large-scale experimental scenarios down to the raw radio level for statistically valid and ***reproducible*** results, similar to a few other fields (e.g., ImageNET [44]). NEXTT also allows one-of-a-kind access to agricultural fields for wireless researchers, who may not otherwise have access. In this unique research area, accuracy and reproducibility of experiments depend on field operations in addition to wireless infrastructure. Successful implementation of technology in fields requires specialized expertise in crop production and water management. To this end, PI Irmak, Bayer, and Valmont provide leadership through SCAL and GLC, making their participation a significant asset to the ***reproducibility*** of Ag-IoAT experimentation operations. Under PM Humphrey’s direction, NEXTT’s design and deployment will be professionally documented for the research community to implement their own instances of NEXTT, with the hope of extending the federation of PAWR testbeds.

**Interoperability:** NEXTT’s cloud-based architecture will allow access down to IQ levels while providing a realistic network backbone that allows ***interoperability*** with various platforms. The use of ExoGENI [38] will enable ***interoperability*** with other NSF-funded network testbeds, COSMOS, and POWDER/RENEW. Authentication to the testbed will be done using the InCommon federated infrastructure and CILogon to create multilateral trust among research entities. To support the required NEXTT functionality, RENCi, together with other members of the team, will implement the necessary Open Resource Control Architecture (ORCA) [37, 42] plugins and resource control policies, provide seamless provisioning control over various heterogeneous resources, and enable users to create complex experiment topologies. NEXTT will also integrate additional APIs created by the PAWR PPO to provide common services across testbeds. Using our BYOR services, researchers can connect their own devices to the platform at different interface levels. We will secure authorization necessary to host radios in existing racks or to mount new boxes on NEXTT physical infrastructure, which may necessitate negotiating access rights with Lincoln, landowners, and/or industry partners. Moreover, the use of standard communication protocols, such as LoRa, Sigfox, NB-IoT, LTE-M, CPRI, eCPRI, and well-defined interfaces for IoAT and other sensors, ensures interoperability for new equipment added as the testbed matures.

**Usability and Programmability:** DPL will achieve *usability* for NEXTT by creating the conductor that will orchestrate all the minute details of the system. When complete, a **novice end user** will be able to collect traffic flow statistics using an intuitive and simple to use interface, while a **power user** will be able to customize every corner of the system. Users will primarily perform four key activities: staging tests, scheduling tests to be executed, monitoring in-progress tests, and retrieving/viewing test results (Fig. 15).

NEXTT 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. Logged in users will see

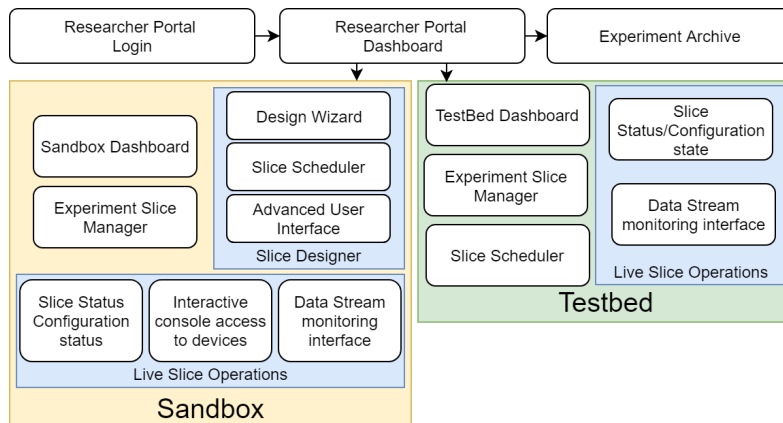


Figure 15: *User Flow Diagram.*

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 breakthrough use-case applications called *NEXTT Profiles*. *NEXTT Profiles* will cover three key use cases: (1) dash/body cam solutions with WatchGuard software and related hardware; (2) wastewater/sewage monitoring solutions with Teledyne sensors and related hardware; and (3) agricultural solutions, including Irrometer sensors, Valmont irrigation systems, Bayer back-end, and related hardware. Profiles will include definitions for the network topology, disk/radio images, research/analysis software, and data files. The definitions can be stored collectively as an RSPEC file, a format used by ExoGENI, or a researcher can upload individual devices and FPGA image files. The wizard will continue to evolve through NEXTT'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. Time scheduling for the virtualized resources is expected to be done using the SLURM [101] resource manager. NEXTT will draw upon established hypervisors such as Kernel-based Virtual Machines (KVMs) [70] and Linux Containers (LXC) [57] for computing resource virtualization, and FlowVisor [91] for network virtualization. We will also deploy our recently proposed solution for wireless resource virtualization [75], which has been purpose-built for heavy-tailed traffic. Users will be able to specify the subset of radio and/or IoAT devices their experiment needs, as well as the time period over which they need access to the devices. Once submitted, jobs to the testbed will run at the scheduled time and do not require user interaction or intervention, although real-time monitoring of the experiments will be allowed. Upon experiment completion, results will be stored on dedicated NEXTT storage and with immediate access for users. The portability and re-usability of the experiments and their individual resources are the critical pillars that allow *programmability*.

**Open Access:** Leveraging the existing SGC portal, users can access NEXTT from <http://nextt.unl.edu/>. All NSF funded researchers will have access at no charge during the five-year funded portion of this project. Non-NSF funded researchers at universities and partnering industry researchers will similarly be granted access. Other researchers will be provided access at non-subsidized rates determined by iLNK. We expect a time allocation of resources to be 40% academic research, 20% operator functions (e.g., maintenance and host

research/education), and 40% industry consortium. Beyond the first five years, iLNK will continue to provide access to subsidized and non-subsidized rates, depending on the industry and academic sponsorship coalition operating at that time. The goal, however, is to continue to provide open access for research purposes and commercial services will not be allowed.

NEXTT will host a heterogeneous set of white- and black-box platforms, including SDRs, mmWave radio, OTA IoAT, underground IoAT, and THz radio with an extensive network architecture to provide open access to platforms from the baseband (IQ-level) to application level. In addition to platform access, the platform is structured to provide open access to results, when possible. We acknowledge the importance of open access to generated data for comparison and further experimentation as well as the importance of protecting the privacy and IP of community members for sustainable industry usage. For example, in applications with Lincoln (wastewater monitoring, police car video streaming) and crop growers (soil moisture monitoring, irrigation automation), it is essential to preserve the privacy of application layer data. To this end, we will preserve the application data at locations that are preferred by the users (e.g., Lincoln’s Chief Information Office, on-site storage for crop fields). For application layer IoAT data, we will follow established practices by Lincoln and Beehive Industries, a Lincoln asset and infrastructure management software company. In the meantime, wireless-related data will be stripped through state-of-the-art anonymization tools for use by researchers.

Other issues with open access to raw radio data are storage capabilities and duration. For open source code, we will utilize public resources (e.g., GitHub). The majority of the trace and offline analysis data will end up at HCC, where we define an expected amount of time for a given amount of data. For differentiated services, we will store data on Attic, HCC’s archival data store, which promises up to five years of backed up storage. For large datasets (e.g., O(PB)), we will utilize a Lustre or Lustre-like file system with the understanding that this will be kept *best effort* but not backed up. HCC currently maintains over 10PB of data in multiple Lustre and Lustre-like file systems, and over seventy public repositories on GitHub.

## Section VI Platform Development Plan

Warren Humphrey (Olsson), project manager, with 25 years experience in SCADA system integration, will lead the platform development efforts. PM Humphrey’s project experience spans design, construction administration, start-up, operations, and maintenance. His hands-on integration experience provides valuable insight into system design, construct-ability, and usefulness to the end users. Through PM Humphrey’s leadership, NEXTT development will follow an agile management framework to mitigate risk by allowing the team to rapidly respond to change with efficiency and effectiveness.

NEXTT’s vision is to build a testbed platform to support use case experimentation. To facilitate this, NEXTT will be developed in phases over a five-year period extended by long-term operation and maintenance. A goal of this magnitude requires a structured and measurable plan, which includes organizing deployment into six tracks to run concurrently over the duration of the project (Fig. 16). Each track represents a technical component designed to support one or more use cases, and when joined, form the NEXTT platform.

The NEXTT story began in 2018 (**Year 0**), with a conceptual design phase and deployment of the Pilot Testbed. The Pilot Testbed includes five SD-DU sites connected on a UNL/Lincoln public fiber network to back-end processing at HCC (See Section II and Facilities). The Pilot Testbed will serve as a springboard for development and deployment of the full NEXTT platform.

Design will begin in **Year 1** with a draft of the project execution plan (PEP) submitted to the PAWR PPO within 30 days of award followed by the final version within 90 days. Design will include elements of conceptual, preliminary, and final design, as detailed in the NSF Large Project Manual, culminating with delivery

| Development Plan Matrix | Design                | Deployment                        |                                                |                                           | Operations                              |
|-------------------------|-----------------------|-----------------------------------|------------------------------------------------|-------------------------------------------|-----------------------------------------|
|                         |                       | Year 1                            | Years 2-3                                      |                                           | Years 4-5                               |
|                         | PEP/<br>Baseline      | Base Functionality                | Early Scaling                                  | Full Scale                                | Sustainability                          |
| Design                  | PEP (Draft and Final) | Maintain and update PEP           |                                                |                                           |                                         |
| Track 1                 |                       | UI/UX / GENI-HCC / SLURM          | Basic feature support                          | Full impl. Multi-user GENI integ.         | Maint. and new features                 |
| Track 2                 |                       | 2 SD-DU / 2 Manhole / User Portal | 10% SD-DUs / Allo VLAN / Manhole / User portal | 100% SD-DUs & manholes / Full user portal | Maint., management, support             |
| Track 3                 |                       | SCAL                              | Gothenburg                                     | Auto Irrigation / Rural Broadband         | Connected Farm / Recruit Farmers        |
| Track 4                 |                       | COTS dev. / Beam tracking         | Multiple mmWs / Multi-user op.                 | Deployment / Mobile video testing         | MU mobile video testing / High mobility |
| Track 5                 |                       | UG Beamforming / LoRa Testing     | MIRF dev. / Multi-carrier UG                   | Teledyne integ. / Deployment              | Operations and fine tuning              |
| Track 6                 |                       | THz TX/RX integration             | Channel charact. / physical layer design       | Pole Integration / Migration to FPGA      | Testing / Refinement                    |

Figure 16: *Development Plan.*

of a final design baseline. Deployment begins with a **vertical slice through the system** to establish baseline functionality to expose risks and rapidly establish a foundation for remaining development and scaling. Initially, we will leverage the Pilot Testbed and the SCAL Ag-IoAT testbeds (illustrating successful collaboration between UNL and Lincoln), and Olsson has and will continue to aide the project through development, permitting, and deployment. Together, these efforts build toward the goal of proactively identifying and addressing challenges, leading to early stakeholder adoption and buy-in within Year 1. In parallel to this foundation will be development and milestones in Mobile mmWave, hybrid MIRF Underground, and THz Radio.

With a functional base platform, next steps in **Years 2-3** include scaling of Smart City IoAT and Ag IoAT to 10% of the goal; beginning integration of **Police Camera Streaming, Underground Infrastructure Monitoring and Agricultural Irrigation Automation, and Rural Broadband Connectivity**; completing remaining distribution sites; adding users to the system; and readying the platform portal for maximum experimentation. Operations (**Years 4-5**), arguably the most important phase, is full integration of all uses cases, platform operations, maintenance, and long-term sustainability made possible through partner commitments and cooperation.

### VI.1 Software Development (Track 1)

DPL will follow a cyclical development process. During the first phase, *Discovery & Design (D&D)*, interactions with stakeholders will help reveal system and user interaction requirements. We will create a shared understanding between the development team and the end users/stakeholders, which will include a series of focused *spikes* that reduce technical risk and further reveal user experience requirements prior to proceeding on with full-scale development.

The project team will then transition to the second phase, *Iterative Delivery (ID)*. The system will be decomposed into services and modules based upon encapsulation of requirements volatility. Once this decomposition is complete, the DevOps environment is configured (which enables automated builds and testing), full-scale software development proceeds in one-week iterations called sprints that progress toward the identified features and milestones. The core MVP of NEXTT's software interface will be complete by the end of Year 1, allowing users rudimentary interactions with nearly every aspect of the system. By the end of Year 2, the MVP of Police Camera Streaming and Underground Infrastructure Monitoring, as well as a complete implementation of the Agriculture Irrigation Automation testbed, will be complete. Year 3 will bring a full implementation of Police Camera Streaming, Underground Infrastructure Monitoring, and Rural Broadband Connectivity. Years 4 and 5 will consist of ongoing maintenance and new feature enhancements driven by feedback from users.

DPL is positioned to support NEXTT in perpetuity and provide a seamless transition of maintenance to other teams (e.g., PAWR PPO) if deemed in the best interest of NEXTT. Regardless of direction, this is handled in the third software development phase, *Team Transition*. There are a fair number of systems related to software development that are concretely defined. Authentication within NEXTT will be accomplished using InCommon [46] federated infrastructure in conjunction with GENI [40] to ensure secure stable access for researchers. Resources will be allocated via the ORCA control framework developed for ExoGENI. External access to both experimental results and RF database will be facilitated by the use of Globus Online [50] and Data Transfer Nodes which HCC currently uses. A 100Gbps capable FIONA DTN and path to Internet2 currently exist from HCC and the Pilot Testbed. This path will be expanded as necessary with the growth in use of NEXTT.

### VI.2 Smart City IoAT and NG-RAN (Track 2)

NEXTT use cases are well positioned to take advantage of existing partnerships and city resources through deployment in conjunction with major city initiatives (Section IV). Smart City IoAT applications for **Police Camera Streaming and Underground Infrastructure Monitoring** use cases will be focused on two areas: Antelope Valley corridor where Lincoln has existing fiber, and 27th Street where VLAN access through Allo will be available. Beginning with the Pilot Testbed as the foundation, the full NEXTT architecture will integrate the core aggregation switch and FPGA server of the pilot, located in SEC, to serve as the primary hub site for NG-RAN. Connectivity for the second-tier NEXTT distribution sites and rural Ag-IoAT sites will be established at SEC, allowing a direct link to the pilot network and computing resources at both SEC and the HCC. With HCC



and SEC online, prioritized shared resources are available to meet needs for scaling to a full production mode while still allowing opportunistic resource use for testing or offline analysis.

Production mode deployment will continue by partnering with GL<sup>2</sup> to deploy 2 new pairs of SD-DU and IoAT radio installations. The SD-DUs will be installed on Lincoln traffic poles and NEXTT will partner with LWWS and Teledyne to design wastewater flow monitoring sensor installation and monitoring application. Initial IoAT locations will be selected where LWWS has existing instrumentation. LWWS has also offered to relocate devices as needed to support NEXTT.

The NEXTT architecture will integrate an experimental spectrum sensing and wireless security testbed with a configurable set of SD-DUs. Every SD-DU in the wireless security testbed will be equipped with basic wireless security protocols, including anti-jamming mechanisms (e.g., frequency hopping, direct-sequence spread spectrum), device authentication mechanisms (e.g., single sign-on authentication), key establishment protocols (e.g., Diffie-Hellman key exchange protocol), and differential-privacy data protection mechanism. The wireless security testbed will be integrated with a security monitoring system that examines the spectrum for DSS and incoming and outgoing network traffic from the testbed resources in order to make sure the experiments are confined in a controlled environment to avoid impacts with other platform users. Malicious behavior emulation service will also be embedded into each SD-DU, which allows SD-DU to emulate a compromised node with the ability of launching different types of cybersecurity attacks. The attack demonstrations conducted in the secure enclaves will not influence other system operations. **Major milestones for Year 1 (MS1):** Integration of Pilot Testbed, final SD-DU and smart city IoAT network design, wireless security testbed design, integration of two SD-DU for camera streaming and two IoAT sites for underground monitoring into the platform, and preliminary use of sites via the user portal.

Year 2 deployment incorporates an additional four SD-DUs and four IoAT devices on Antelope Valley and two SD-DUs and two IoAT radios at newly connected traffic intersections. *One Allo VLAN will be contributed to the PAWR project*, allowing NEXTT radio access at any point on Allo's 1000+ mile private fiber optic network. **MS2:** Scale to 10% of the system on-line, Go-Live at distribution sites (MT and NIC), and addition of four SD-DU and four IoAT sites.

By Year 3, the basic functionality of the system will be established with preliminary testing on a subset of sites. Remaining development will be on scaling the number of sites to 100% and completing the deployment partnerships with GL<sup>2</sup>, Allo, and LWWS. Year 3 deployment will be largely construction based activities as the remaining SD-DUs and IoAT radios sites, including manhole flow instrumentation, are procured, installed, and commissioned. Special considerations will be placed on working relationships with Lincoln utilities to ensure construction stays on schedule and within budget (Section VIII). Other activities include full integration of mmWave and underground wireless into the platform. **MS3:** Full integration and go-live on all SD-DU, IoAT, and wastewater manhole sites; commissioning of full functionality for **Police Camera Streaming and Underground Infrastructure Monitoring** use cases.

The final phase of NEXTT, **Years 4 and 5**, is dedicated to operations and maintenance activities to support platform, users, and experiments. Programs and chains of responsibility will be established for field repair, preventative maintenance, and technical support. **MS4-5:** BYOR deployments, refinement of the LWWS infrastructure monitoring and LPD body camera streaming, programs maintenance and technical support.

### **VI.3 Ag-IoAT and Rural Broadband Connectivity (Track 3)**

Over the last decade, PIs Vuran and Irmak have operated a remote agricultural IoAT testbed in a maize/soybean cropland rotation at SCAL. This testbed will be NEXTT's first rural site and will be operational in Year 1. The testbed has already been used by UNL researchers to design wireless underground sensor-aided automated irrigation control solutions and has provided real-time information. It will be equipped with remotely programmable radios integrated with UNL's wireless underground sensor platforms as well as OTA IoAT devices to provide real-time soil moisture and wireless experimentation information. This site design will be replicated in Bayer's GLC fields to create another site in Year 2. One of the unique advantages of SCAL is that PI Irmak has been working closely with researchers and scientists from other disciplines (plant pathology, soil fertility, weed science, plant breeding, entomology, agricultural economy, and other disciplines) and working toward integration

of all these disciplines with engineering principles and fundamentals to create next generation and efficient agricultural production systems. The scientists and researchers from these diverse disciplines conduct extensive research at SCAL and are committed (verbal commitments) to utilize NEXTT to establish and/or enhance their wireless data gathering capabilities from agricultural research fields.

In Year 1, an NG-RAN cell will be deployed at Clay Center for connectivity with fields in SCAL and advanced wireless underground radio solutions with software-defined radios (Section III) will create a completely concealed UT platform design in SCAL (also see Track 5). To the best of our knowledge, this deployment will be the first large-scale remotely accessible wireless underground platform in agricultural fields. **MS1:** SCAL Center-pivot retrofit and Ag-IoAT deployment with advanced wireless devices.

During Year 2, Bayer's GLC fields will be deployed. At SCAL, Ag-IoAT automated irrigation applications will be conducted for the first seasonal operation. While the investigation, development, and testing of platforms will primarily be carried out at SCAL and GLC, successful platforms may be implemented into some of NAWMN's [60], [63] functions (see Facilities). Accordingly, in this year, we will also start recruiting farmer fields near SCAL to establish a rural connectivity testbed with connected weather stations. **MS2:** Gothenburg deployment, 5G-grade Ag-IoAT roll-out, and Ag-IoAT automated irrigation operations.

In Year 3, first and second seasonal Ag-IoAT automated irrigation operations at SCAL and Gothenburg, respectively, will be conducted with industry partners. Further, we will integrate hybrid UG wireless radio platforms with the deployments to enhance capabilities and create a connected farm infrastructure. Accordingly, automation applications will be supported in this infrastructure. Moreover, rural broadband connectivity experiments (see Track 6) will be conducted in cooperation with our industry partners (e.g., SDT, Valmont, and Bayer). **MS3:** Ag-IoAT automated irrigation operations in a consecutive seasons and rural broadband connectivity testbed implementation.

Year 4 operations will include second and third year operations of connected farm operations and Ag-IoAT automated irrigation, respectively. Based on our previous experience with NAWMN, we expect an increase in recruitment of new agricultural fields for both Ag-IoAT and rural broadband connectivity testbed implementations. Some of the NAWMN partners/collaborators are located in some of the most rural communities in the U.S., providing a unique platform for implementing NEXTTs functions to enhance rural community well-being. **MS4:** Rollout for rural broadband connectivity testbed for community users and expansion of Ag-IoAT deployments.

In Year 5, concurrent operations of automated irrigation and connected farm applications will be conducted. For agricultural technology development, evaluation of new solutions in multiple growing seasons is essential. Therefore, it is important for NEXTT to sustain these operations for multiple years. In this year, we will also upgrade field devices for next-generation technologies in agricultural fields.

#### **VI.4 mmWave Platform Development (Track 4)**

NEXTT mmWave platform will be developed along with beamforming and resource allocation algorithms, which will be implemented and tested on the mmWave platforms developed with COTS components, including phased array antennas, up/down converters, SDR modules, and GPS receivers. **PIs Ekici and Koksali** from OSU have led projects focused on development, deployment, and testing of MIMO systems ranging from vehicular [25] to large-scale surveillance systems [48], [79]. They have been jointly working on novel mmWave architectures and algorithms for the last five years. They have also lead projects on foundational and application aspects of wireless networking and communication supported by NSF, DoD, DoE, and industry.

In Year 1, the mmWave development platform will be formed based on COTS components, including antenna arrays, up and down converters, and USRPs. Preliminary implementation and testing of physical layer algorithms will be performed on this experimental setup. The implementation of advanced beam tracking algorithms will also be started during the first year. **MS1:** COTS development platform, physical layer algorithms, implementation and testing of a single-link mmWave system.

Year 2 will be dedicated to the expansion of the mmWave system from a single-link system to a multi-user platform. Multiple COTS platforms will be linked to each other. The focus of the second year will be the implementation of user tracking, scheduling, and link maintenance algorithms in a multi-user setting. User

mobility tests will also be performed during this period. **MS2:** Multi-user COTS platform, implementation of networking algorithms, mobile multi-user mmWave testing.

Year 3 will be dedicated to migration of the mmWave to the mmWave SDR platform. While the efforts in Years 1 and 2 focus on the development of algorithmic aspects of our solution, the migration effort will focus the efficient implementation of these solutions for field deployment, and the initial integration of WatchGuard cameras. **MS3:** Migration to the mmWave SDR platform, physical layer and network algorithm tests, mobile multi-user tests for the field deployment, camera integration as data source.

In Year 4, field deployment of the mmWave system will be performed. First use cases involving mobile platforms will be tested in uncontrolled environments. WatchGuard cameras and the mmWave system will be tested on LPD-provided platforms. Interfaces to accommodate research community contributions will be defined, and first tests open to partners will be performed. **MS4:** Mobile user tests in real-life scenarios, rural broadband deployment, system interfacing to manage and implement outside contributions and test cases.

Year 5 will be dedicated to refinement of multi-user mobile mmWave solutions, development of future-proof network management and maintenance procedures, and general testing of solutions provided by the research community. Outreach to other academic and industry stakeholders will be performed to include them in the NEXTT ecosystem to foster community growth beyond the project duration.

## **VI.5 Hybrid MIRF Underground Platform Development (Track 5)**

UNL-patented RF underground communication technologies [100] will be enhanced with novel long-range soil-adaptive beamforming and high-throughput underground multi-carrier solutions [85, 86] for extensive connectivity in underground pipes and crop fields. In addition a unified, hybrid, remotely accessible platform that integrates PI Akyildiz's MI transceivers with UNL's enhanced RF transceivers will create a new class of hybrid underground radios for underground sensing applications and research in communication in challenging environments.

In Year 1, remotely programmable *UT devices* will be developed. UNL's existing *wireless underground* radios at SCAL [45, 100] will be retrofitted with SDRs. Moreover, based on our industry partners' overlapping interests of IoT standards (Bayer, Valmont, Small Data Tech, IntelliFarm, Irrrometer), OTA radios will also be integrated with soil sensors for a testbed with a continuum of OTA-UG connectivity. Moreover, soil-adaptive beamforming array for extended-range RF-communication will be developed. **MS1:** UG beamforming, LoRa testing, and SCAL retrofitting.

In Year 2, hardware development of hybrid MI/RF radios will be finalized. We have already built pure MI-based devices with a temperature sensing component, an energy harvesting unit, an ultra-low power MCU MSP430G2553, and a MI-based transceiver. To enable RF communications, we will integrate UNL's RF mode with components of a sub-GHz transceiver, an underground antenna, a matching circuit between the transceiver and the antenna. Moreover, we will enhance MIRF design with our multi-carrier UG design for high data-rate communication. **MS2:** MIRF development and multi-carrier UG.

In Year 3, the hybrid device will be integrated with the Ag-IoAT testbeds in SCAL and Gothenburg for field experiments. Moreover, high data-rate MIRF radios will be integrated with Teledyne's advanced pipeline monitoring sensors for deployment in manholes. **MS3:** Teledyne sensor integration, field deployment, high-level use case integration.

In Years 4 and 5, extensive testing for the hybrid underground IoAT platform will be conducted for fine tuning the platform components. Moreover, tutorials will be provided to NEXTT users for UG wireless concepts and usage. **MS4-5:** Testing, platform refinement, outreach and education.

## **VI.6 THz Radio Development (Track 6)**

NEXTT will leverage the state of the art and preliminary works developed by our team to create the first multi-km THz X-Haul to date. Each node in THz X-Haul will integrate the following elements (Figure 17): The LO will be generated by a synthesizer at 75 GHz (itself consisting of a 25 GHz generator, a frequency tripler, and a power amplifier at 75 GHz), followed by a high-power frequency tripler and a broadband mixer at 225 GHz, developed by NASA JPL. These are replicas of the prototypes used for the aforementioned long-range THz communication

experiment. Two 3-inch horn lens antennas per node with 40 dB gain will be mounted. For the generation of the IF signal in transmission and the processing of the IF signal in reception, high-performance FPGAs will be utilized. The physical and data link layer functionalities implemented in the FPGAs will include: 1) framing of the network-layer information; 2) addition of the link-layer header; 3) implementation of the error control strategy; 4) addition of the physical layer header, including a preamble for time, frequency and phase synchronization, followed by a pilot/training sequence for channel estimation; and 5) modulation/demodulation, pulse shaping, filtering and power control.

In Year 1, the focus will be on developing a high-power THz transmitter and receiver evolved from the team's initial prototypes (Fig. 11), and installing the nodes on the THz site. In this first technology demonstrator, commercial equipment (e.g., Keysight Arbitrary Waveform Generators (AWG) and Digital Storage Oscilloscopes (DSO)) will be utilized to generate and process the transmitted and received IF signals, respectively.

**MS1:** Transmitter and receiver fabrication and testing with commercial equipment.

In Year 2, extensive measured data sets will be utilized to characterize the THz channel and the impact of weather conditions across the broad bandwidth of interest. Based on the channel behavior, different techniques for channel estimation and equalization will be developed, implemented and tested on the THz front-ends with the AWG and DSO for off-line signal processing. Similarly, the performance of different modulation and coding strategies as well as time, frequency and phase synchronization schemes will be tested. **MS2:** Enhanced Tx and Rx development, channel characterization and physical layer testing.

In Year 3, the efforts will be on porting the selected signal processing schemes to an FPGA-based system able to support real-time signal processing. For this, PI Jor-net will leverage the know-how acquired while developing and utilizing the NSF-CRI-funded X60 Testbed (Award #1629929). The pole will be designed to accommodate a new custom-designed synthesizer for the LO (as opposed to commercial PSGs), custom-designed power supplies, an FPGA for baseband signal processing and compact NASA JPL up&down converters and antenna, within a weather proof recipient. By the end of Year 3, the THz X-Haul will be connected to the optical backhaul. **MS3:** Migration to FPGA-based system, pole design and installation.

In Years 4 and 5, the emphasis will be on utilizing the testbed, assessing the impact of different environmental and operational factors on the THz X-Haul performance when collecting real data, and opening the platform to those users who have already expressed their eagerness in validating ongoing work in terms of THz channel modeling and physical and link layers design. **MS4-5:** Operation, maintenance and enhancement of the setup.

## Section VII Sustainability Plan

NEXTT will address forward thinking research challenges on at-scale research platforms, increase education about wireless technologies and data networking, accelerate academic-industry-community partnerships, and advance commercialization. Moreover, NEXTT users will be encouraged to contribute their newly developed communication protocols to the NEXTT library for other application developers to leverage for new, more advanced applications. In this way, NEXTT will continue to evolve and increase its value to the research community and to industry. The long-term sustainability of NEXTT is essential for fully enabling experimental exploration of robust new wireless devices, communication techniques, networks, and services that will revolutionize the nation's wireless ecosystem. We view the initial development of NEXTT as a *strategic investment in a start-up operation*. Consequently, if selected for award, NEXTT will treat the grant as a venture capital investment from NSF and the Industry Consortium for five years and thereafter the wireless platform will operate on a self-sustaining basis and be supported largely by user fees. NEXTT's operation and business plan is structured to reflect this vision to support sustainability well into the future.

**Anticipated Funding Streams:** NEXTT's long-term success will rely heavily on research, industry, and community users. Access to NEXTT nodes will be available for research and testing license/use with fees based on the cost to operate the infrastructure. On a local level, Nebraska EPSCoR and the Nebraska Research Initiative

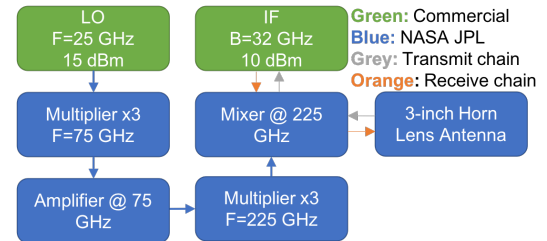


Figure 17: THz transmit and receive chains.



sponsor seed grant programs that catalyze public-private research collaborations and provide proof-of-concept support for fully developed research teams. Nebraska is an EPSCoR state, among 27 other U.S. states, that is eligible for the NSF EPSCoR Research Infrastructure Improvement Program Track-1 (RII Track-1). As indicated in the letter of support from Nebraska EPSCoR, NEXTT's infrastructure, particularly the rural components, will be a strong contender for the RII Track-1 to improve the infrastructure and maintain its sustainability.

Beyond Nebraska, we will encourage academic users, in particular, to utilize seed fund programs at their organizations to support research that will utilize NEXTT infrastructure. We anticipate a majority of academic users will have federal funding, including from NSF. As active relevant projects of letters of support writers indicate, NEXTT will be able to support evaluations of research activities funded through NSF investments of over \$38M. In addition, we will apply to major equipment infrastructure programs like NSF's Major Research Instrumentation program, as relevant. This type of funding will support new functionality to the project as user fees will cover routine and incremental upgrades and other maintenance. Further, new technology from vendors may be possible to incorporate in return for access to the Pilot Testbed. Project partners will leverage these resources for sustainable upgrades to NEXTT's platform and research. We also will generate revenue from advertisements on the testbed interface. We anticipate that companies interested in reaching wireless researchers, as well as companies that will be the users of the testbed, will be interested in posting advertisements.

**Pricing Strategies:** In Year 1, NEXTT will seek out partnerships with wireless carriers, equipment manufacturers, software/protocol vendors, advanced sensor manufacturers, utility system operators, and network security/encryption system operators. User fees will be generated on a "per node class, per site" basis with operating cost divided into a 70/30 split between industry and research community partners. User fees will start in Year 3, increase incrementally during Years 4-5, and will be in full effect by Year 6. The most powerful argument in favor of charging user fees early during the development phase is the discipline of the marketplace, i.e., fees increase accountability to the users receiving services.

Lincoln's GL<sup>2</sup> and LTIS Broadband projects will continue to add node locations and capacity to the system through 2025, which will enable sustainable scalability beyond project duration. Depreciation will play a critical factor in determining user fees, as well as the operating costs for the maintenance and administration of business. In addition, there will be a need for upgrades to the system as technology evolves. A percentage of the collected user fees will cover the cost of upgrades to the system. Costs of monitoring and routine administration may be reduced by incorporating student workers. This activity will be educational training for the student, while providing redundancy and affordability to the NEXTT workforce.

Early users of the testbed will provide preliminary data to determine and update operational cost estimates, user classes, and price sensitivities. User classes will be defined based on expected service time of the user and service type (e.g., urban IoAT, agricultural IoAT, mmWave, UG, THz platform). Price sensitivities will be estimated to better understand how different user types value the service provided by the testbed. We plan to offer our base services free of charge to Industry Consortium members by issuing time credits, and we will allocate complimentary advertisement slots for them. Further, to solidify our customer base, we will offer discounted long-term contracts for early users of the testbed during the development phase, i.e., during Years 1-5.

**Plans for Attracting New Users:** To attract industry users within close proximity to NEXTT, we will leverage a unique environment provided by the fledgling technology startups that are expanding the "Silicon Prairie" and strong small business support from the Nebraska Department of Economic Development (NEDED) (see letter of support). For example, industry partners based in Nebraska will have access to NEDED Academic Research and Development Grants, which provide funding to local businesses for applied research and development projects with a Nebraska college or university. In this sense, local industry can conduct research using NEXTT *for free*, which is a major incentive for local industry participation while providing sustainable income to NEXTT. We will work with our partners and industry contacts to identify other similar sources of research funding across the Midwest and beyond to support industry users from outside Nebraska.

**Software Sustainability:** Any successful software system will undergo maintenance and extension throughout its life. Unfortunately, most software systems do not age well and become fragile and rigid under active development and modification. DPL has made significant progress in reversing this trend by developing and adopting a methodology that results in systems that enable change. The key attributes of these systems are (1)

a highly cohesive, loosely coupled system of modules and services; (2) decomposition of modules based upon encapsulation of the future changes in the system; and (3) automated unit and integration testing that enables effective regression of changes. The result is a system that is easier to understand and comprehend as a software developer, easier to change, easier to test, and can live long into the future as a cutting edge solution. We will utilize these principles to support software sustainability of NEXTT components.

## Section VIII Risk Mitigation Plan

**Methodology:** The risk management methodology detailed in the Project Management Institute's *Project Management Book of Knowledge* will guide deployment and use of the platform. Primary delivery risks include: (1) *schedule* risks, (2) *scope* risks, and (3) *resources/budget* risk. NEXTT's risk management methodology includes risk identification and subsequent quantification of the risk impact, risk response, and risk monitoring and control throughout its lifespan.

**Testbed and Operations:** Critical to our design, deployment, and operational risk mitigation plan is NEXTT's pilot testbed, which currently offers researchers five radio sites and two data sites across a traffic light on a Lincoln public street and UNL campuses. This pilot is enabling us to identify and find solutions to risks as they occur. The testbed is also evidence of our ability to integrate a wireless platform with HCC's multi-user accounting and managing systems for multiple users. We are successfully leveraging HCC's 15 years of experience in cluster computing, high performance computing, and now, wireless networking. In addition, UNL's Information Technology Services has vast experience with risk mitigation and addresses it in many ways (e.g., *change control process*, incident alert notification and command team structure, redundant infrastructure to support technology services). If an incident occurs, 24 x 7 staff are prepared to follow an alert notification process to provide awareness by text or email. UNL and Lincoln provide redundancy for services, systems, and infrastructure. Data centers are staffed and monitored 24 x 7. These sites provide redundant power, generators, and/or environmental controls to ensure the environment is secure and resilient.

**Software Risks:** DPL, Lincoln's largest outsourced software product development organization, employs patterns and practices that ensure each project achieves a successful outcome regardless of the participating individuals and identified risks. NEXTT's main risks within the software platform are the integration points that interact with third party systems and platforms. Specific risk points include: ExoGENI, SLURM, GNURadio, physical radios, Single Sign On (SSO) authentication via InCommon, and integration with WatchGuard, Teledyne, Bayer, and Valmont devices/software, which introduce risk in the form of potential scope modification. Some of these risks will be mitigated by dedicated technical personnel at our local community partners. DPL's development patterns will encapsulate each of the risk points into loosely coupled architectural blocks. This encapsulates requirement volatility and minimizes uncertainty as well as hidden assumptions. Overall, the process ensures visibility into project progress and obstacles, enables project and requirements agility, and implements a layered approach to quality, effectively mitigating any risk whether they are known up front or identified later.

**Urban Deployment:** Commissioning new sites will be a critical to full deployment, and our approach will be carefully planned with alternate contingencies. Site selection will meet specified criteria, including power, network connectivity, and height for antenna installation. Ideal locations are existing traffic signal poles where the enclosures already have power and a fiber optic network. When space in traffic cabinets is insufficient, radio equipment will be located in a dedicated external enclosure. If the desired pole is not accessible, an alternate adjacent pole will be evaluated or a location chosen. Key is the permitting process—all new site installations will be Lincoln approved and include structural analysis of any pole mounting installations, as we have gone through in the Pilot development. The time required to gather the necessary documents and prepare approval drawings, pole ID numbers, manufacturer submittals, and as-built drawings will be reduced because all the key players are already part of the team. Lincoln owns the fiber and power, Valmont manufactured the majority of the poles, and Olsson has worked with both on projects over many years. Once permits are obtained, installation and testing will occur through Commonwealth Electric, which has a successful history of working with partners.

**Rural Deployment:** For a decade, PIs Vuran and Irmak have operated an Ag-IoT testbed in rural Nebraska, identifying and addressing risks associated with deploying and operating wireless prototypes in challenging environments. Moreover, *recruiting private land owners for experimental usage is an extremely challenging*

*task.* PI Irmak's experience establishing and managing NAWMN, the largest irrigation, crop production, and water management network in the U.S. (Fig. 7(b)), uniquely positions us in this regard. Further, NEXTT's THz X-haul links are based on NASA JPL's state-of-the-art Schottky-diode-based technology for high-power THz devices. This technology has been deployed for gas monitoring without fail for almost a decade in satellites orbiting the Earth. In the unlikely event any of the elements in the THz front-ends stop working, they will be replaced by a spare unit stored at UNL. The modular design of the front-ends allows for a replacement of the module within minutes.

## **Section IX Management Plan, Organizational Structure, and Project Staffing**

UNL will provide the institutional leadership to ensure NEXTT's success, as evidenced by its successful track record of managing large research programs such as the Antarctic Geological Drilling Project (NSF #034248); a Materials Research Science and Engineering Center (NSF #1420645); and a Tier-2 site for the Compact Muon Solenoid experiment (CMS) (NSF #1343486), a large particle detector experiment based at the Large Hadron Collider (LHC) at CERN in Switzerland. HCC, an integral partner in the management of NEXTT user accounts and infrastructure, is a national leader in the Open Science Grid community and the home of U.S. CMS at UNL.

UNL's technical and operational capacity is aligned with Lincoln's next-generation wireless infrastructure, and will leverage recognized talent and emerging infrastructure (as evidenced in the Pilot Testbed) to establish large-scale urban and rural platforms that can serve as novel testbeds for catalyzing sophisticated wireless research activities. UNL and Lincoln are joined by core partners OSU, UB, and GT, which bring complementary expertise in mmWave, THz, and underground communications research and applications; Olsson, which brings decades of project management experience; DPL, which is expert at software development; and industry users, which inform use case identification and deployment. This diverse partnership complements the PPO's vision and goals for advanced wireless research and establishes NEXTT as an integrated whole that is greater than the sum of its parts, which is essential to enable game-changing advancements in wireless technologies.

### **IX.1 Project Leadership and Organizational Structure**

Project leadership will be shared by Dr. Mehmet Can Vuran (UNL) and Mr. David Young (Lincoln). The Program Directors will be supported by a broader network of experts who bring intellectual breadth and depth, practical experience, and the team-based structure needed to realize NEXTT's vision (Fig. 18).

**Program Director:** PI Vuran, Susan J. Rosowski Associate Professor of Computer Science and Engineering at UNL and director of the Cyber-Physical Networking Laboratory (CPN), has been recommended for promotion to full professor. His case is under review and it is expected that his promotion will take effect in May 2019. PI Vuran earned an NSF CAREER award for "Bringing Wireless Sensor Networks Underground." In 2014, 2015, and 2016, he was named one of the world's most highly cited researchers by Thomson Reuters. PI Vuran is developing next-generation underground sensors and automating irrigation decision-making for agriculture via NSF funding, and in addition to a remote Ag-IoT testbed in a maize/soy bean rotation fields at SCAL that he operates with PI Irmak, his team has designed and operated three extensive network testbeds: a vehicle to barrier communication testbed during live vehicle crash tests at UNL; a correlation-aware cognitive radio network (CoRN) testbed (Lincoln, NE), and a Sandhill Crane Migration Monitoring testbed (Wisconsin-Florida migration route). He has extensive experience leading cutting-edge research projects and efforts to bring academic research to the market. In 2012, he was selected to participate in the NSF Innovation Corps (I-Corps) given the potential of wireless underground sensor networks he developed to give agricultural producers real-time information about soil moisture and changing conditions to enable more efficient irrigation. PI Vuran is the technical lead for the Lincoln Smart Gigabit Community project funded through U.S. Ignite, and under his leadership, the Ignite Lincoln team developed a citywide gigabit wireless network to take advantage of unused wireless spectrum and allow radios to both broadcast on and listen to multiple frequencies. He is ideally positioned to co-lead NEXTT with PI Young.

**Co-Program Director:** Co-PI Young, Lincoln's Fiber Infrastructure and Right of Way Manager, co-leads the Lincoln Smart Gigabit Community project with PI Vuran and has played an instrumental role in helping to make the Pilot Testbed operational. His experience in wireless broadband is exceptional. In 2012, he was

hired by Lincoln to design its LTIS program. As a consultant, he developed Tulsa’s Conduit System (2008); Sacramento’s Wireless Master Plan (2015); Branson’s Spirit of ’76 Broadband Infrastructure (2016), and Kansas City’s Broadband Master Plan (2017). In 2018, he was appointed by FCC Chairman Pai to serve as the Vice Chair of the FCC Broadband Deployment Advisory Committee, a panel of industry experts that provides policy advice on how to accelerate the national deployment of wireless and wireline broadband infrastructure.

**Senior Team Leaders:** To ensure a well-rounded and efficient management structure, three senior team leaders will report directly to the Program Directors: Mr. Warren Humphrey (Olsson), project manager responsible for testbed deployment; Prof. Steve Goddard (UNL), responsible for general operations and outreach; and Prof. Suat Irmak (UNL), responsible for field operations. Each is expert in his respective field (see biographical sketches). The senior team, with input and guidance from the NEXTT Executive Advisory Board and User Advisory Group, will lead NEXTT.

**Advisory Groups:** The Executive Advisory Board will be chaired by Dr. Ian Akyildiz, a world renowned expert in wireless communications and the Internet of Things as well as a visionary leader in the research community. Other members will include Prof. Guru Parulkar, Executive Director of *Open Network Foundation* [12], a nonprofit trade organization funded by companies like Deutsche Telekom, Facebook, Google, Microsoft, Verizon, and Yahoo driving transformation of network infrastructure and carrier business models; Dr. Ilya Baldin, Director of RENCI; Dr. Ronnie Green, UNL Chancellor; and the Honorable Chris Beutler, Mayor of Lincoln, as well as Chief Executive Officers or Chief Technology Officers of industrial collaborators. The User Advisory Group will consist of the most frequent users of NEXTT. Members will be selected from represented groups: academic researchers, industry partners, and community users (e.g. Paulson Farms, see support letter). User Advisory Group will provide feedback on the usability and accessibility of NEXTT, which will help the Executive Advisory Board and directors set priorities for deployments and enhancements.

**Other:** The remainder of the management structure is shown in Fig. 18. The Use Cases are led by industry partners, who will develop applications to utilize NEXTT wireless breakthroughs and infrastructure. Wireless breakthroughs are required (and expected) in three main areas: mobile mmWave communications, led by Drs. Ekici and Koksai (OSU); underground communications, led by Drs. Vuran (UNL) and Akyildiz (GT); and THz communications, led by Drs. Jornet (BU) and Akyildiz (GT). Each is a world-renowned expert in their respective fields (see biographical sketches). The Infrastructure component consists of four modules: software, led by Mr. Doug Durham (DPL’s Chief Technology Officer), who has 30 years of software engineering and development experience in aerospace, defense, healthcare, manufacturing, e-commerce, and Internet network services; GENI, led by Dr. Ilya Baldin (RENCI), who is the PI of a recent NSF award to “to update, adapt, operate and maintain the existing GENI infrastructure”; computation, led by Dr. Swanson and Mr. Attebury (UNL), who direct and manage HCC; and wired infrastructure, led by Dr. Ramamurthy (UNL) and UNL’s Information Technology Services organization. PI Ramamurthy has extensive experience designing, deploying, and operating research testbed platforms, including the Great Plains Environment for Network Innovations (GpENI), a Layer-2

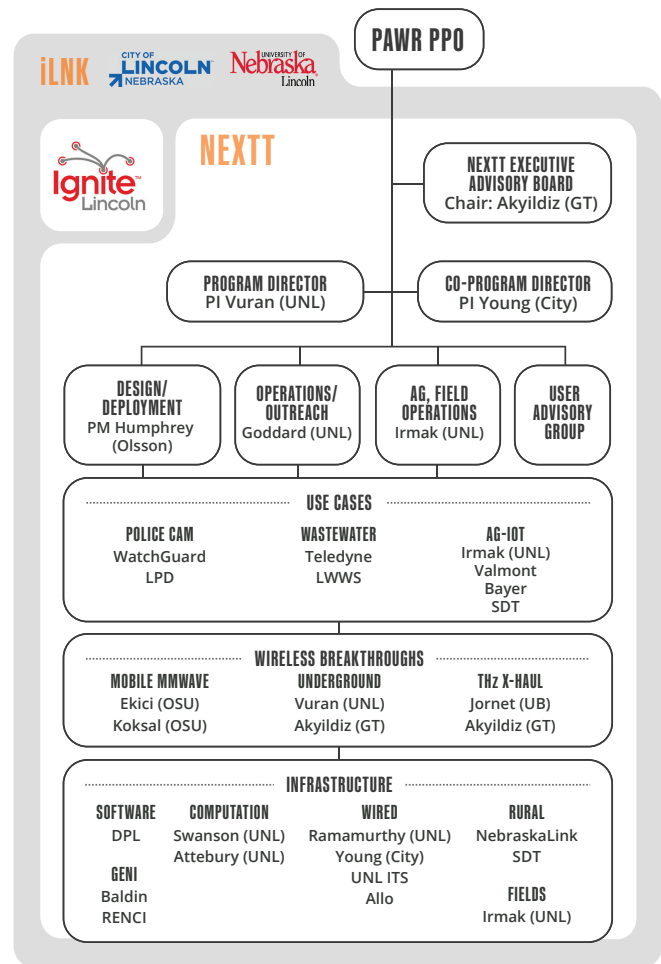


Figure 18: *NEXTT organizational structure.*

network testbed in Nebraska, Kansas, and Missouri, funded by NSF and GENI. He also helped design and deploy a Nebraska-wide real-time groundwater monitoring network (funded by USDA RMA) connecting 54 wells.

NEXTT will be administered through iLNK, a UNL-Lincoln Interlocal Agency. iLNK (in formation) will function as a coordinating body with oversight of and responsibility for executing finances; infrastructure development; maintenance and operations; relationships between partners; and research activities. iLNK will be responsible for funds management and administration and will collaborate with UNL's Office of Sponsored Programs (OSP) to ensure all financial compliance and reporting obligations are met. iLNK will partner with OSP to develop a business plan that, in the long term, will enable earned revenues in excess of operational costs to be strategically reinvested into exploratory research efforts or infrastructure enhancement. In the short term, iLNK will ensure the necessary infrastructure is in place on time and on target.

## IX.2 Project Management Approach

NEXTT's project management approach is based on NSF's Large Facilities Manual guidelines. While NEXTT's size is not large enough to warrant strict adherence to the manual, key principles will be followed at an appropriately scaled level, as suggested in Section 2.7 of the manual. These key principles will be in project management, budgeting, cost estimating, communications, and reporting. Special attention will be placed on the tracking, calculating, and reporting of earned value. Olsson, which will help to oversee project management, is uniquely qualified to lead this requirement. NEXTT software development management will draw from DPL's relevant methods including the Agile Scrum methodology, and make use of Rally to manage and track the platform development and workflow processes.

NEXTT's leadership team will define the priority list of platform functions and features and organize these to fit within the phasing and track structure (Section VI). These functions and features will be built in iterative cycles within each track, ultimately integrating into the core platform. This process will allow functions and features to be revised or enhanced as more of the platform's depth is uncovered through the previous iterations, enabling NEXTT to come online in a manner and timeline compliant with PPO requirements. NEXTT will work aggressively to meet prescribed programmatic benchmarks and to be responsive to the research needs of the advanced wireless community, doing so in a manner that is operationally lean. Once proof-of-concept and the value proposition are established, the goal is to build a broad base of users and generate sustaining revenues to enable NEXTT to function as a long-term, national research resource that enables U.S. discovery and innovation.

## Section X Contributions of Key Personnel in the Past Five Years

In Fig. 19, we show how connected the core partners have been via partnerships over the last five years.

PI Vuran has an established track record of building and maintaining wireless network testbeds in challenging environments as is evidenced by his development of sustainable underground system solutions in agricultural crop fields and his technical leadership for the Ignite Lincoln project. He has longstanding collaborations with NEXTT key personnel from Lincoln (Young), UNL (Irmak, Goddard, Ramamurthy, Yan, Attebury, Swanson), OSU (Ekici), GT (Akyildiz) and with NEXTT industry partners (Valmont, Olsson, Allo). Further strengthening this collaborative network are PIs Vuran and Irmak's NSF grants, which enable deployment of next-generation wireless underground sensing solutions in agricultural fields for automated irrigation decision-making. The applications of this work impact both wireless network research and agriculture, and necessitate strong relationships with industry, including Bayer and Valmont.

PI Young established and leads Lincoln's LTIS Broadband and Small Cell initiatives. LTIS, a nationally recognized model for public-private partnership in the deployment of city-scale broadband infrastructure projects, has 12 industry partners, deployed more than \$220M in broadband infrastructure, and generates more than

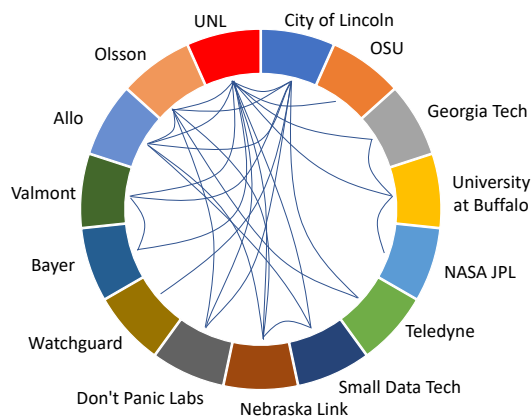


Figure 19: *Social network of NEXTT.*



\$1.2M in annual revenue. Lincoln and UNL have existing joint fiber sharing agreements under LTIS. Further, WatchGuard and Lincoln completed an initial deployment of in-car and body cameras for LPD in 2016, and increased deployment in 2017 and 2018. In 2016, PI Young partnered with Valmont, Olsson, and Verizon to develop the Lincoln Small Cell pole, a low cost, rapid deployment, replacement street light pole for small cells.

PM Humphrey has led SCADA systems projects for Lincoln Wastewater, Lincoln Water, Lincoln Solid Waste, and UNL Facilities and managed multiple advanced control system projects, including \$1.5M in phased control system upgrades at Lincoln's wastewater resource recovery facilities.

PI Irmak founded and leads NAWMN, which, with more than 1,400 Nebraska farmers and 2.5 million acres of farmland, is the most comprehensive agricultural water management network in the U.S. NAWMN's focus on enhancing agricultural water use efficiency through underground wireless systems demonstrates PI Irmak's unique track-record to build and manage large-scale multi-stakeholder partnerships. He also leads the Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBLUX), which operates 11 advanced flux towers for long-term measurements of terrestrial ecosystem water vapor and energy fluxes and environmental biophysical properties for a range of agro-ecosystems. NEBLUX is one of the largest flux networks in the U.S. that is operated by a single research laboratory. SCAL has some of the most advanced engineering research fields in the country in crop physiology, energy flux towers, climate vs. surface interactions, and irrigation systems, and PI Irmak has extensive experience in managing large-scale field research projects in collaboration with farmers, state and federal partners, and industry.

UNL has conducted more than 250 projects with Bayer and was a major driver behind their decision to locate their Water Utilization Center and for Bayer's decision to locate its Global Wheat Breeding Program headquarters in Nebraska. Valmont, the largest manufacturer/seller of center pivot irrigation systems, is a long-term partner and its founder invested millions in the creation of the university's Water for Food Institute.

Our collaboration history in wireless urban environments is evidenced by Lincoln's designation by U.S. Ignite as a Smart Gigabit Community (Ignite Lincoln), on which PIs Vuran and Ramamurthy serve as technical leads and PI Young serves as community lead. Ignite Lincoln enables UNL, Lincoln, and Allo to develop advanced wireless infrastructure in public spaces. Leveraging Ignite Lincoln and UNL funds, we successfully deployed the NEXTT Pilot Testbed to enable next-generation wireless network experimentation. The Pilot Testbed offers researchers multiple radio and data sites across a traffic light on a Lincoln public street and UNL campuses. Bringing the Pilot Testbed online required significant teamwork and experience in planning, deployment, and operations by UNL (PIs Vuran, Ramamurthy, Goddard, Swanson, and Information Technology Services), Lincoln (PI Young), Olsson (PM Humphrey), and Valmont. SDT has a history of collaborating with NebraskaLink and CropMetrics.

PIs Akyildiz and Jornet design, model, and patent THz nano-devices. In collaboration with nanomaterials and nanoelectronics experts, and with support from AFOSR, PI Jornet has demonstrated ability to fabricate, transfer, and pattern graphene-based nano-antenna arrays for THz communications, and he leads an NSF CRI project to build an integrated testbed for *true* THz communications. This testbed, together with his active collaboration with NASA JPL, places us in an advantageous position. Similarly, PIs Ekici and Koksall have a track record of collaboration on topics ranging from nano-communication to vehicular and mmWave communication systems. They lead the communication research at OSU's DoT Crash Imminent Safety University Transportation Center. PI Koksall's NSF grant supports his research on experimentation for mmWave propagation and developing a suitable low-delay transmission controller. They collaborate to develop low-energy low-delay mmWave communication algorithms to support high mobility use cases.

PIs Ramamurthy and Swanson collaborated with UNL's Information Technology Services to deploy 100G connectivity to the Internet2 backbone on a NSF-funded Campus Cyberinfrastructure (CC-NIE) project. They also collaborate on a NSF CC\*DNI Integration project for OpenFlow development. Since 1999, PI Swanson has directed HCC, which supports more than 1,000 users and is a contributor and collaborator with OSG, an international coalition of computing and storage sites. HCC has supported the research activities of the local and national CMS community as a "Tier-2 computing center" since 2005, one of eight such Tier-2 sites across the U.S. HCC staff are part of a team that is further tasked to support T3 sites nationwide.

The NEXTT team is eager and ready to open the next page in Internet of All Things experimentation.

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