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Mehmet C. Vuran
University of Nebraska-Lincoln, mcvuran@cse.unl.edu

Abdul Salam
University of Nebraska-Lincoln, asalam@cse.unl.edu

Rigoberto Wong
University of Nebraska-Lincoln, rwong3@unl.edu

Suat Irmak
University of Nebraska-Lincoln, suat.irmak@unl.edu

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Internet of Underground Things: Sensing and Communications on the Field for Precision Agriculture

Mehmet C. Vuran, Abdul Salam, and Rigoberto Wong

Cyber-Physical Networking Laboratory
Department of Computer Science & Engineering
University of Nebraska-Lincoln, Lincoln, NE 68588
Email: {mcvuran, asalam, wong}@cse.unl.edu

Suat Irmak

Department of Biological Systems Engineering
University of Nebraska-Lincoln, Lincoln, NE 68583
Email: sirmak2@unl.edu

***Abstract*—The projected increases in World population and need for food have recently motivated adoption of information technology solutions in crop fields within precision agriculture approaches. Internet of underground things (IOUT), which consists of sensors and communication devices, partly or completely buried underground for real-time soil sensing and monitoring, emerge from this need. This new paradigm facilitates seamless integration of underground sensors, machinery, and irrigation systems with the complex social network of growers, agronomists, crop consultants, and advisors. In this paper, state-of-the-art communication architectures are reviewed, and underlying sensing technology and communication mechanisms for IOUT are presented. Recent advances in the theory and applications of wireless underground communication are also reported. Major challenges in IOUT design and implementation are identified.**

I. INTRODUCTION

World population will increase by 32 percent in 2050, doubling the need for food. Yet today, up to 70 percent of all water withdrawals are due to food production. This demands novel technologies to produce *more crop for drop*. USDA Agricultural Resource Management Survey (ARMS) is the primary source of information on the financial condition, production practices, and resource use of America's farm businesses and the economic well-being of America's farm households. ARMS data show that *precision agriculture* has become a widespread practice nationwide. In Fig. 1, adoption rates of major precision agriculture approaches (bars) along with the total precision agriculture adoption rate (line) are shown for corn for each year of USDA ARMS publication (USDA ARMS 2015 version was under development at the time of this writing). It can be observed that adoption rate of precision agriculture for corn increased from 17.29 percent in 1997 to 72.47 percent in 2010 with similar trends observed for other crops such as soybean and peanuts. Aside from presenting a growing trend in the usage of precision agriculture in corn production, it is evident that as new technologies emerge, they are widely adopted by farmers.

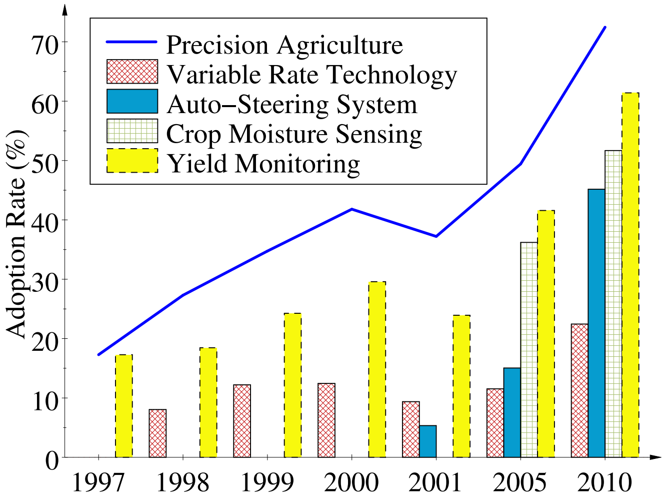

Fig. 1: Precision agriculture technology adoption in corn production (USDA ARMS Data).

Among the various precision agriculture techniques, crop yield monitoring is the most widely adopted technique (61.4 percent). In addition, guidance and auto-steering system adoption jumped from 5.34 percent in 2001 to 45.16 percent in nine years. Use of equipment and crop location information enables precise control with auto-steering systems which reduce production and maintenance costs and reduces repetitive field work for farmers. Despite the drastic increase in adoption rates of other techniques, variable rate technology (VRT) adoption has been relatively steady, where adoption rate increased from 8.04 percent in 1998 to only 11.54 percent in 2005. Adaptive application of resources like fertilizers, pesticide, and water promises significant gains in crop production but requires accurate and timely information from the field. It can be observed that only after the adoption of recent crop moisture sensing technology, VRT adoption doubled to 22.44 percent in 2010. During the same period, crop moisture sensing adoption increased from 36.21 percent in 2005 to 51.68 percent in 2010.

It is clear that the success and adoption of variable rate technology depends on advancing soil monitoring approaches. Despite being the most recent precision agriculture technology, crop moisture sensing has become one of the most adopted

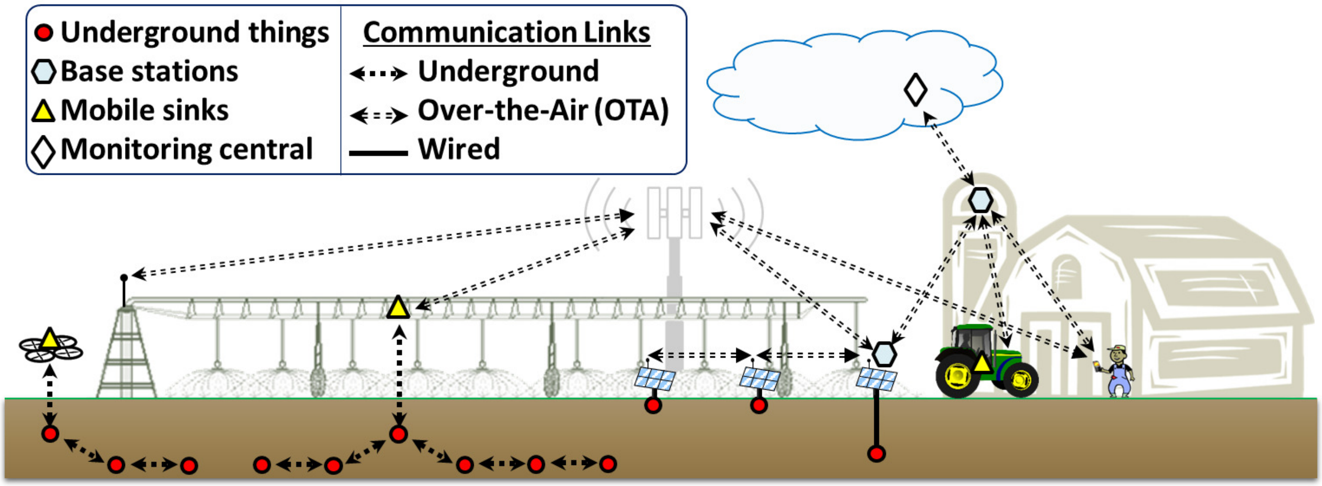

Fig. 2: IOUT Paradigm in Precision Agriculture.

practices. Yet techniques are still limited to manual data collection or limited field coverage. Most recently, the need for real-time in-situ information from agricultural fields have given rise to a new type of IoTs: Internet of underground Things (IOUT). IOUT represents autonomous devices that collect any relevant information about the Earth and are interconnected with communication and networking solutions that facilitate *sending the information out of fields* to the growers and decision mechanisms.

IOUT is envisioned to not only provide in-situ monitoring capabilities (e.g., soil moisture, salinity, and temperature), but when interconnected with existing field machinery (irrigation systems, harvesters, and seeders) enable complete field autonomy and pave the way for better food production solutions. In IOUT, communications can be carried out through the soil and plants from underground devices, and information acquired from the field can be sent to cloud through the Internet for real-time decision making.

Due to to the unique requirements of the IOUT applications; i.e., information from soil, operation in remote crop fields, wireless communication through plants and soil, and exposure to elements; existing over-the-air (OTA) wireless communication solutions face significant challenges because they were not designed for these circumstances. As such, IOUT also gives rise to a new type of wireless communications: *wireless underground (UG) communications* [1], [2], where radios are buried in soil and wireless communication is conducted partly through the soil. Integration of UG communications with IOUT will help conserve water resources and improve crop yields [3], [4]. Moreover, advances in IOUT will benefit other applications including landslide monitoring, pipeline assessment, underground mining, and border patrol [2], [5], [6], [7], [8], [9], [10].

This paper presents Internet of Underground Things for the design of precision agriculture solutions. We first discuss functionalities, architecture, and components of IOUT. Then, we present sensing and communication technologies of IOUT along with existing solutions. We conclude by presenting IOUT testbeds and discussing challenges of IOUT.

II. IOUT ARCHITECTURE

IOUT will consist of interconnected heterogeneous devices tailored to the crop and field operations. Common desirable functionalities of IOUT are:

- *In-situ Sensing:* On board soil moisture, temperature, salinity sensors are required for accurate localized knowledge of the soil. These sensors can be either integrated on the chip along-with other components of the architecture, or they can be used as separate sensors that can be connected to the main components through wires.
- *Wireless Communication in Challenging Environments:* Communication components of IOUT devices are either deployed on the field or within the soil. For OTA communication, solutions should be tailored to the changing environment due to irrigation and crop growth. In addition, any system on the field is exposed to natural elements and should be designed to sustain challenging conditions. Underground communication solutions, while mostly shielded from the environment, require the ability to communicate through soil and adjust its parameters to adapt to dynamic changes in soil.
- *Inter-Connection of Field Machinery, Sensors, Radios, and Cloud:* IOUT architecture should link a diverse multitude of devices on a crop field to the cloud for seamless integration. Accordingly, IOUT architecture will not only provide collected information but will also automate operations on the field based on this information.

Based on these main required functionalities, a representative IOUT architecture is illustrated in Fig. 2, with the following components.

- *Underground Things (UTs):* An UT consist of an embedded system with communication and sensing components, where a part of or the entire system resides underground. UTs are protected by weatherproof enclosures and, in underground settings, watertight containers. Buried UTs are protected from the farm equipment and extreme weather conditions. Sensors typically include soil temperature and moisture sensors, but a wide range of other

TABLE I: Existing IOUT Systems.

Architecture	Sensors	Comm. Tech.	Node Density
Automated Irrigation System [11]	DS1822 (temperature) VH400 (soil moisture)	OTA, ZigBee (ISM)	One node per indoor bed
Soil Scout [4]	TMP122 (temperature) EC-5 (soil moisture)	UG, Custom (ISM)	Eleven scouts on field and a control node
Remote Sensing and Irrigation Sys. [12]	TMP107 (temperature) CS616 (soil moisture) CR10 data logger	OTA, Bluetooth (ISM)	Five field sensing, one weather station
Autonomous Precision Agriculture [6]	Watermark 200SS-15 (soil moisture) Data logger	UG, Custom (ISM)	Up to 20 nodes per field
SoilNet [13]	ECHO TE (soil moisture) EC20 TE (soil conductivity)	OTA, ZigBee (ISM)	150 nodes covering 27 ha
IRROMETER 975 IRROmesh (http://www.irrometer.com/)	200TS (temperature) Watermark 200SS-15 (soil moisture)	OTA, Custom (ISM) OTA, Cellular	Up to 20 nodes network mesh
John Deere Field Connect (https://www.deere.com/)	Leaf wetness Temperature probe Pyranometer Rain gauge Weather station	OTA, Proprietary OTA, Cellular OTA, Satellite	Up to eight nodes per gateway

soil- or weather-related phenomena can be monitored. Existing communication scheme include Bluetooth, ZigBee, satellite, cellular, and underground. A UT using Bluetooth [12] or underground wireless [6] can communicate over 100 meters, commercial products at ISM-band can cover three times larger distances, whereas longer-distance connectivity is possible through cellular or satellite. Considering the relatively large field sizes, nodes can be configured to form networks capable of transferring all the sensed information to a collector sink and self-heal in the event that nodes become unreachable (e.g., Irromesh). Nodes are generally powered by a combination of batteries and, if on field, solar panels. Cost of UTs is expected to be relatively inexpensive as they are deployed by the multitude [11].

- *Base stations* are used as gateways to transfer the collected data to the cloud. They are installed in permanent structures such as weather stations or buildings. Base stations are more expensive as they are better safe-guarded and have higher processing powers and communication capabilities [11].
- *Mobile sinks* are installed in equipment that move around the field periodically or as required, such as tractors and irrigation systems [6]. When weather conditions are favorable, turning on an irrigation systems only for data retrieval purpose is expensive. Alternatives unmanned vehicles such as quadrotors or ground robots.
- *Cloud services* are intended to use for permanent storage of the data collected, real-time processing of the field condition, crop related decision making, and integration with other databases (e.g., weather, soil).

A summary of the existing academic and commercial architectures is provided in Table I. In most commercial products, OTA wireless communication is utilized, where the UT includes a high-end soil moisture and temperature sensor, connected to a tower in the field with cellular or satellite communication capabilities. Consequently, measurements generally represent a single point in the field and redeployment of the equipment is needed after planting and before harvest each season to avoid damages by the farming machinery. In addition, commercial products based on OTA wireless mesh networks and academic approaches featuring underground wireless communication have been emerging.

Availability of such a diverse range of communication architectures makes it challenging to form a unified IOUT architecture with the ability to fulfill agricultural requirements seamlessly. This is further complicated due to the lack of standard protocols for sensing and communication tailored to the IOUT. In the following, we explain in detail the sensing (Sect. III) and communication (Sect. IV) mechanisms with a focus on desired characteristics of IOUT for real-time sensing and effective communications.

III. SENSING

The main functionality of OUT is real-time sensing. An overview of sensing technologies is presented next.

1) Soil Moisture: Soil moisture (SM) sensors have been used for decades in crop fields to measure water content. Important SM measurement methods are described below:

- Gravimetric sampling is a direct and standard method of measuring SM. It is used to determine the volumetric water content of the soil. This method determines SM by a ratio of soil's dry mass to the wet soil mass including the pore spaces. It requires manual sampling and oven drying of soil samples taken from the field.
- Resistive sensors such as granular matrix sensors work on the principal of electrical conductivity of water and measuring resistance changes based on soil water content. This method requires calibration of sensors.
- Capacitive sensors measure SM based on changes in capacitance of soil due to water content variations. Capacitive sensors, which are generally of higher accuracy than resistive sensors but cost more, are being used by commercial UTs.
- Ground Penetrating Radars (GPR) are based on the absorption and reflection of electromagnetic waves. Im-

Fig. 3: Soil moisture sensors: Top row: Gravimetric, resistive (Watermark), capacitance, Bottom Row: GPR, TDR, neutron probe.

pulse, frequency sweep, and frequency modulated technologies are used in SM sensing. This method is used to to measure near-surface soil moisture (up to 10 cm).

- Neutron scattering probes and gauges use radiation scattering techniques to measure SM by estimating changes in neutron flux density due to the water content of the soil and are the most accurate soil moisture probes used in fields. They require specific licenses to be used.
- Gamma ray attenuation, time-domain reflectometry (TDR), and frequency-domain reflectometry (FDR) are other popular SM measurement approaches.

Common SM sensors used in fields are shown in Fig. 3. SM sensors are buried at depths of 5 cm to 75 cm in soil depending on the crop type and root depth. SM data obtained from these sensors is used to create soil moisture maps which help real-time decision making. SM sensors have been deployed in fields with increasing frequency. For example, the Nebraska Agricultural Water Management Network [14], [15], was established with only 20 growers in 2005 and currently serves over 1,400 growers to enable the adoption of water and energy conservation practices using SM sensors.

2) Other Soil Physical Properties: In addition to soil moisture sensing, other soil properties can be measured to populate the soil map such as the organic mater present in the soil, acidity (pH), percentage of sand, clay and and silt particles, and nutrients such as Mg, P, OM, Ca, base saturation Mg, base saturation K, base saturation Ca, CEC, K/Mg, and Ca/Mg ratios. In-situ, real-time measurement of these properties still face challenges due to size, cost, and technology limitations.

3) Electrical Conductivity and Topography Surveys: The ability of soil to conduct current is described by soil electrical conductivity (EC). Coupled with field topography (elevation and slope), EC data gives better insight into the crop yield. EC (through contact and no-contact methods) is used to determine the amount of nitrogen usage, water holding and cation-exchange capacity, drainage, and rooting depth. EC maps are used to classify the field into zones. Then, precision agriculture practices such as variable rate irrigation, variable rate seeding, nitrogen, yield, and drainage management are applied based on zoning.

IV. WIRELESS CONNECTIVITY

Connectivity solutions for IOUT can be classified as in-field communications and cloud connectivity as discussed next.

A. *In-field Communications*

In-field communication solutions integrate UTs and other communication entities on the field. Most commercial solutions utilize OTA communications, whereas IOUT are expected to feature wireless underground communications.

OTA Communications: Existing communication devices rely on LAN, cellular, and satellite technologies. For short-range communication and networking, license-free standards such as Bluetooth, ZigBee, and DASH7 are used in ISM bands. More recently, regulatory restrictions are relaxed by the FCC through new rules that allow the use of TV white space frequencies in farms (Order No. DA 16-307 Dated: Mar 24, 2016), where interference with other licensed devices is not expected. The major challenge for OTA communications is the lack of studies about the impacts of crops and farm environment on wireless propagation and associated tailored solutions to farms. Most devices used on farms were not designed to be used on agricultural fields and hence, suffer significantly.

UG Communications: UG communication solutions enable complete concealment of UTs, which decrease operation costs and impacts from external elements. For a buried UT radio, two types of communication scenarios arise. Aboveground communications involve communication between UTs and aboveground devices. Underground communication is carried out between UTs. Furthermore, due to the soil-air interface, aboveground communication links are not symmetric and need to be analyzed in terms of underground-to-aboveground and aboveground-to-underground communication. In Fig. 4, the path loss of these links are shown as a result of field experiments [6]. It can be observed that practical underground link distances are still limited to allow for practical multi-hop connectivity. Yet, communication ranges of up to 200 m is possible for aboveground communications.

For UG communications, the communication medium is soil, which impact communication success in six main ways as discussed next.

(1) Soil Texture and Bulk Density: EM waves exhibit attenuation when incident in soil medium. These variations vary with texture and bulk density of soil. Soil is composed of pore spaces, clay, sand, and silt particles. Relative concentration of these particles result in 12 soil textural classes. Water holding capacity of each soil type is different because of its pore. For example, lower water holding capacity of sandy soil leads to lower attenuation and high RMS delay spread, whereas higher water holding capacities of silt loam and silty clay loam soils result in low RMS delay spread and higher attenuation [7].

(2) Soil Moisture: The effective permittivity of soil is a complex number. Thus, besides diffusion attenuation, EM waves also suffer absorption by soil water content and its

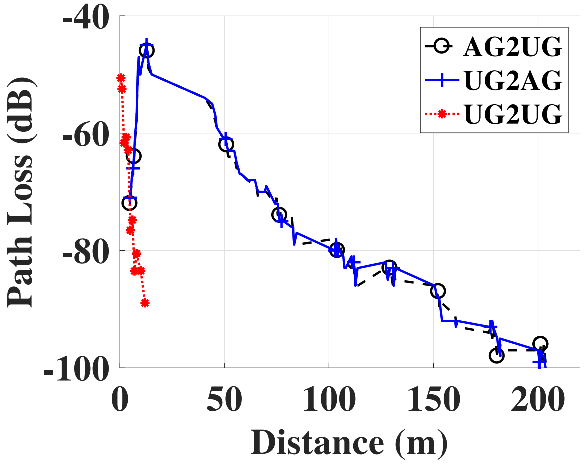

Fig. 4: Communication from soil.

variations. Soil dielectric spectra and its conductivity depends on the soil moisture. The relative dielectric constant range of dry soil is between 2-6 and its conductivity ranges from 10^{-4} to 10^{-5} Si/m, where soils at near-saturation level have a relative dielectric constant in the range of 5-15 and conductivity between 10^{-4} to 10^{-5} Si/m [16]. Coherence bandwidth of the underground channel is limited to a few hundred KHz range [8], which limits data rates. Coherence bandwidth also varies with soil moisture, making design of advanced techniques challenging.

(3) Distance and Depth Variations: Sensors in IOUT applications are usually buried in the top sub-meter layer. Thus, in addition to distance, channel quality depends on deployment depth because of the impacts of the soil-air interface, which causes refraction of EM waves. Nodes at higher burial depths experience higher attenuation.

(4) Antennas in Soil: When an antenna is buried, its return loss characteristics change due to the high permittivity of soil [17]. Moreover, with the variation in soil moisture and hence soil permittivity, the return loss of the antenna varies with time too. Changes in return loss results in variations in resonant frequency, which is shifted to the lower spectrum, and system bandwidth, creating additional challenges for UG communication.

(5) Frequency Variations: The pathloss caused by attenuation is frequency dependent because of dipole relaxation associated with water. Generally, lower frequency spectrum has lower attenuation, because at higher frequencies, water absorption plays a dominant role. In addition, when EM waves propagate in soil, their wavelength shortens due to higher permittivity of soil than the air. Therefore, channel capacity in soil is also a function of operation frequency [17].

(6) Lateral Waves: For two UTs, wireless underground communication is conducted through three major paths: direct, lateral, and reflected waves [7], [6]. Direct and reflected waves reside completely in soil and therefore, suffer from the challenges above. On the other hand, lateral waves travel partly on the soil-air interface in air, experiencing the lowest attenuation. Lateral waves plays an important role in extending underground communication ranges.

B. IOUT and Cloud

Due to limited processing power and energy considerations, data processing and decision making are not generally conducted locally. Depending on privacy considerations, field information can be stored in a private database, provided to the public databases, or shared with other users. There are online marketplaces where big data sets and agricultural apps are used to analyze a region and make decisions to maximize crop yield. Additionally, in-situ SM sensors can be linked to national soil moisture databases for complete, accurate, and comprehensive information of soil moisture. With the support of cloud services, real-time visualization and decision support can be provided.

On the other hand, in the absence of storage or processing constraints, base stations on the fields can pull meteorological data from a weather service or soil information from a national service, fuse this information with in-situ data from UTs, and control the farming equipment. To have a fully automated system, farming equipment should include a controller that can be accessed remotely.

Irrespective of in-situ or cloud processing, the main challenge is the integration of heterogeneous systems. Moreover, reliable data transfer from field to cloud, and cloud to farm will constitute an important functionality of the IOUT cloud architecture. This functionality will not only help link fields over vast geographical areas to the cloud, but will also facilitate local farms to use this data for assessment and improvement of crop yield.

V. IOUT TESTBEDS

In this section, we present an overview of testbeds which facilitate IOUT developments for system-wide and communication-specific challenges.

A. An Agriculture Field Testbed

IOUTs can be used to ascertain the amount of water and fertilizer to be applied using an irrigation control system. An IOUT testbed has been deployed on the South Central Agricultural Lab (SCAL) in Clay Center, Nebraska. The testbed covers a 41 acres of research field where an advanced center pivot irrigation system was installed in 2005 to research long-term dynamics of variable rate irrigation and fertigation, crop water and nutrient uptake, water stress and yield relationships, develop crop production functions, and associated numerous topics under full and limited irrigation and rainfed settings [18]. In this testbed, a mobile sink is installed on one of the controller towers. The current configuration includes two antennas facing opposite directions allowing the reception of data from nodes that are over 200 meters away. A solar panel provides sustainable energy in the field. 10-16 UTs are deployed in the field. Each UT is capable of measuring soil temperature and soil moisture from four external sensors buried at depths of 1, 2, 3, and 4 feet. UTs are powered by lithium-ion batteries and protected by a watertight enclosure. The spatio-temporal real-time information from UT is fused at the mobile sink and sent to the cloud using 4G communications. The cloud communicates with the center pivot controller for automated irrigation control.

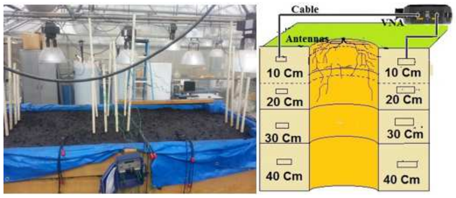

Fig. 5: The Indoor Testbed [7].

B. Wireless Underground Communication Testbeds

Agronomy and Horticulture Greenhouse in the University of Nebraska-Lincoln east campus houses two wireless underground communication testbeds. An outdoor testbed consist of a grid of 4 x 2 underground nodes with an above-ground node that can be moved to any location to study aboveground-to-underground, underground-to-aboveground, and underground-to-underground communications behavior. Underground nodes are connected through power-over-Ethernet (POE) to reprogram and power the nodes. This setup provides flexible underground experimentation by eliminating the need for replacing the power sources, exposure of the equipment, and the constant removal and burial of the node.

An indoor testbed has been designed and developed inside the greenhouse which supports dynamic soil moisture control for wireless underground communication experiments [7]. The testbed is made of 100 inches long, 36 inches wide and 48 inches high wooden box with drainage system to hold 90 cubic feet of packed soil (Fig. 5). Antennas are buried at different depths and distances for controlled wireless communication experiments. Moreover, testbed based on magnetic induction (MI) underground communications has been developed in [3]. This testbed includes coils buried in the underground in lab settings. MI wave guide effects and 3-D coils are investigated using this testbed in different soil configurations.

VI. RESEARCH CHALLENGES

Challenges in design and implementation of a precision agriculture based IOUT are highlighted in this section.

- Due to dynamic changes in the communication medium in soil, UTs should be able to cognitively adjust their operation parameters such as operation frequency, modulation schemes, error coding schemes for adaptive operation. Due to the close interactions with soil, these solutions should be tailored to UG communications instead of adopting existing OTA solutions [7], [8], [6]. Impacts of soil physical properties, soil moisture on UG communication should be modeled.
- Improving UTs with more complex functionalities will lead to higher energy consumption and faster battery depletion. Thus, improvements in energy efficient operation, sustainable energy sources, and energy harvesting are major challenges.
- Low-cost and multi-modal soil sensors that can sense soil physical properties in addition to moisture are required. While moisture provides valuable information for irrigation decisions, soil chemicals need to be sensed in-situ for variable rate fertigation applications.

VII. CONCLUSIONS

We introduced Internet of Underground Things (IOUT) for real-time decision making in agricultural fields. We have presented complete architectures for precision agriculture based IOUT. We have also analyzed the sensing and communications as the main component of the Internet of Underground Things. Challenges to the realization of IOUT are highlighted, and testbed designs for IOUT realization are presented.

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