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Internet of underground things in precision agriculture: Architecture and technology aspects

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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. Moreover, recent advances in the theory and applications of wireless underground communication are also reported. Finally, major challenges in IOUT design and implementation are identified.

Keywords: Internet of things, Wireless underground communications, Sensing, Precision agriculture, Soil moisture

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1. Introduction

World population will increase by 33% in 2050, doubling the need for food [124]. Yet today, up to 70% 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 recently 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 maize 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 maize increased from 17.29% in 1997 to 72.47% 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 maize production, it is evident that as new technologies emerge, they are widely adopted by farmers.

Among the various precision agriculture techniques, crop yield monitoring is the most widely adopted technique (61.4%). In addition, guidance and auto-steering system adoption jumped from 5.34% in 2001 to 45.16% 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% in 1998 to only 11.54% 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% in 2010. During the same period, crop moisture sensing adoption increased from 36.21% in 2005 to 51.68% in 2010.

It is clear that the success and adoption of VRT depends on advancing soil monitoring approaches. Despite being the most recent precision agriculture technology, crop moisture sensing has become one of the most adopted practices. Yet techniques are still limited to manual data collection or limited field coverage.

2. A new paradigm: IOUT

Most recently, the need for real-time in-situ information from agricultural fields have given rise to a new type of IoT: 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 more efficient 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 the cloud for real-time decision making.

IOUT applications have unique requirements; 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* [68,152], where radios are buried in soil and wireless communication is conducted partly or completely through the soil. Integration of UG communications with

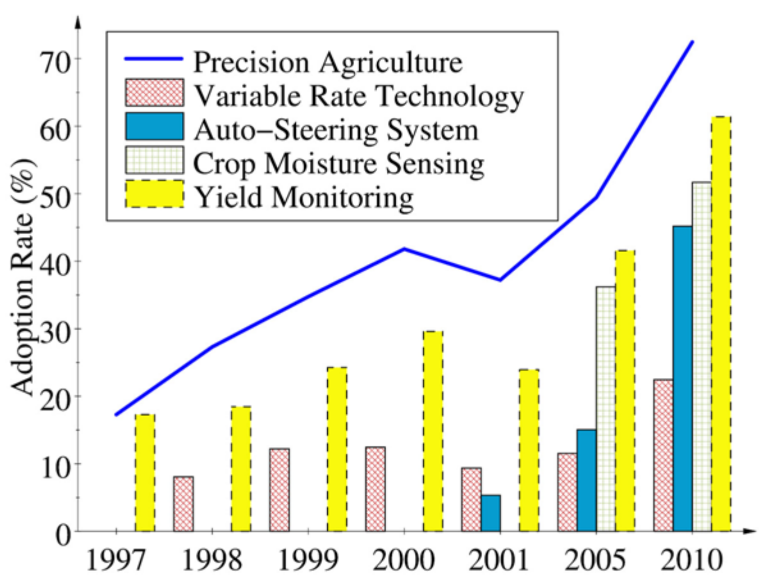

Fig. 1. Precision agriculture technology adoption in maize production (USDA ARMS Data).

IOUT will help conserve water resources and improve crop yields [143,145]. Moreover, advances in IOUT will benefit other applications including landslide monitoring, pipeline assessment, underground mining, and border patrol [67,69,71,84,94,102,106,115,132,138,142,146,150,152,159].

This paper presents IOUT for the design of precision agriculture solutions. We first discuss functionalities, architecture, and components of IOUT. In Section 4 and 5 , we present sensing and communication technologies of IOUT. In Section 6 , we list IOUT testbeds and existing solutions. We conclude by discussing challenges of IOUT.

3. 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.
- *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. Over the air communication is used to store the data on a more secure and accessible service/ device. 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:* It is desirable that IOUT architecture links 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.
- Real-time Decision Making: Information about soil and crop conditions should be available to the managers and decision support systems for real-time decision making at each level.
- Mobility: IOUT will have seamless support for both fixed and mobile devices with backing of short-term and long-term communications.

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, wild rodents, and extreme weather conditions. Sensors typically include soil temperature and moisture sensors, but a wide range of other soil- or weather-related phenomena can be monitored which will be discussed in detail on Section 4. Existing communication schemes include Bluetooth, ZigBee, NFC, Wi-Fi, Sigfox, LoRa, LoRaWAN, satellite, cellular, and underground. A UT using Bluetooth [105] or underground wireless [86] 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 [24]). 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 [96].
- *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 [96].

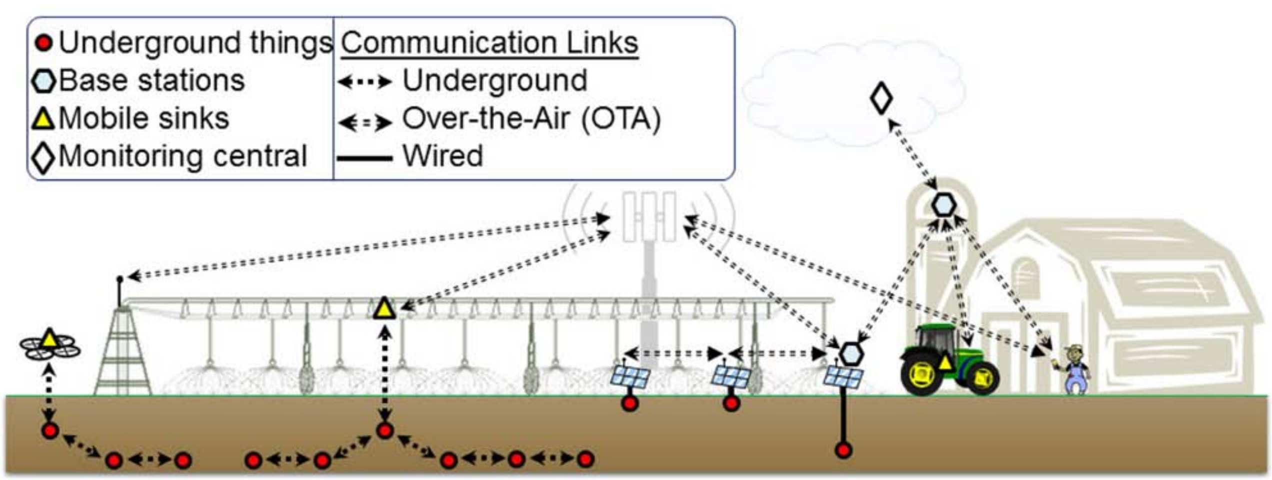

Fig. 2. IOUT paradigm in precision agriculture.

- *Mobile sinks* are installed in equipment that move around the field periodically or as required, such as tractors and irrigation systems [86]. Since irrigation machinery advance at a slow pace, the soil data is received ahead of time allowing instant adjustment on the water application rate. On the other hand, when weather conditions are favorable, turning on the irrigation equipment only for data retrieval purpose is expensive. An alternative is to use unmanned aerial vehicles (UAVs) such as quadrotors or ground robots to retrieve the measurements.
- *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).

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 (Section 4) and communication (Section 5) mechanisms with a focus on desired characteristics of IOUT for real-time sensing and effective communications.

4. Sensing

The main functionality of IOUT is real-time sensing. Sensing has led to adoption of technology in the precision agriculture and it also enables improved efficiency of agricultural production and practices [127]. An overview of sensing technologies is presented next.

Soil moisture: Soil moisture (SM) sensors have been used for decades in crop fields to measure water content. Automated technologies have largely replaced the use of hand-held/manual soil moisture technologies because of difficulties associated with taking manual soil moisture readings in production fields in remote locations. In the last decade, wireless data harvesting technologies have been developed that provide managers and users real-time access to soil moisture data which has resulted in more effective water management decision-making. 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 [91].

- Resistive sensors [50] 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 for accurate SM reading.
- 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) [66,98] are based on the absorption and reflection of electromagnetic waves. Impulse, frequency sweep, and frequency modulated technologies are used in SM sensing. This method is used to measure near-surface soil moisture (up to 10 cm).
- Neutron scattering probes [87,92] and gauges use radiation scattering techniques to measure SM by estimating changes in neutron flux density due to the water content of the soil are the most accurate soil moisture probes used in fields. They require specific licenses to be used.
- Gamma ray attenuation [90], time-domain reflectometry (TDR) [128], and frequency-domain reflectometry (FDR) [139] 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

Fig. 3. Soil moisture sensors: Top row: Gravimetric [91], resistive (Watermark) [50], capacitance [17], Bottom Row: GPR [98], TDR [128], neutron probe [92].

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 [99,101], was established with only 20 growers in 2005 and currently serves over 1400 growers to enable the adoption of water and energy conservation practices using SM sensors. In addition to in-situ soil moisture sensors, other soil moisture data sources are Soil Climate Analysis Network [49], US Climate Reference Network [60], TAMU North American Soil Moisture Database [53], Soil Moisture and Ocean Salinity [48, NASA North American Land Data Assimilation System [27], and NASA Soil Moisture Active Passive [46]. These databases contain soil moisture and temperature information of vast geographical areas and augment the Web Soil Survey (WSS) [63], which collects and classifies the US soil information by region.

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) [135], percentage of sand, clay and silt particles [137], and nutrients such as Mg, P, OM, Ca, base saturation Mg, base saturation K, base saturation Ca, CEC, K/Mg, and Ca/Mg ratios [104,110,113]. In-situ, real-time measurement of these properties still face challenges due to size, cost, and technology limitations.

Yield monitoring: Yield monitoring provides spatial distribution of crop yield at the end of a growing season and is used make long-term decisions about agriculture operations [108,118]. Yield monitors are usually installed on farm equipment and automatically collects yield data during harvesting. More specifically, mass flow sensors are installed on grain containers to record grain inflow along with location (e.g., Force Sensor by Ag Leader). The collected data is analyzed using geographic information system (GIS) tools such as ArchInfo, Mapinfo, and Environment System Research International tools.

Electrical conductivity and topography surveys: The ability of soil to conduct current is measured through soil electrical conductivity (EC) [116]. Coupled with field topography (elevation and slope), EC data provides an 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. EC mapping can be done using apparent electrical conductivity (ECa) [88], visible-near infrared reflectance spectroscopy (VNIR) [75], and electromagnetic Induction (EMI) [141] approaches.

An array of commercial tools are available, e.g., Veris 3100 [61], EC400 sensors combined with GPS systems [107] are used for EC mapping.

Weather and environmental sensing: Weather and environmental sensors are used to sense soil and air temperature, direction and speed of winds, and other environmental effects such as rainfall, solar emissions and humidity. For example, John Deere has introduced sensors to assess these phenomena in their commercial Field Connect solution [25]. Availability of this information is useful for real-time and fully informed precision agriculture decisions. A mesoscale network (MesoNet), consists of nodes for weather and environment sensing, spanning over a large geographic area. MesoNet [34] is used to observe major changes in weather patterns, and when combined with IOUT sensing can be used to provide real-time weather information at the farm level.

Soil macro-nutrients sensing: Macro-Nutrients such as nitrogen, potassium, and phosphorous are vital for the crop growth. The assessment of these nutrients helps to determine the fertilizer impact and future applications. Optical sensing is based on reflectance spectroscopy to measure the reflection and absorption by these macrosimulation [104,110,113]. To detect nitrate and sulfate concentration in natural water resources, a sensing method using planar electromagnetic sensors has been developed in [121]. This method is used to sense nitrate and sulfate levels by correlating the impedance of the sensor array with the concentration of these pollutants. It has been shown that sensor impedance decreases with increase in concentration of these chemicals [121]. Electrochemical, VIS-NIRS spectroscopy, and ATR spectroscopy are the major soil macro-nutrients sensing approaches. These soil macronutrients sensing approaches are limited to sense one desired ion because membrane used in these methods only responds to one ion [113]. To achieve concurrent multi-ion sensing, a major challenge is to form a detector array for soil macro-nutrients sensing [104].

Remote sensing: Remote sensing based approaches uses electromagnetic waves which interact with soil and plants in precision agriculture. These approaches work on the measurement of intensity of reflected components of the electromagnetic waves as these interact with soil and plants [120]. Spatial resolution of remote sensing techniques is a major issue; however, when combined with in-situ IOUT sensing approaches, they may result in fine resolution, which can be used to produce field maps for analysis and decision making in precision agriculture. Examples of these include soil moisture, yield [72], texture [140], pesticides applications [95], and nutrient field maps [2,112,120]. Remote sensing has also applications in satellite data fusion, crop structure and condition monitoring.

Other precision agriculture technologies: A myriad of other technologies is playing vital role in the precision agriculture practices. Here we briefly mention these technologies as useful IOUT tools. These include precision planting, geolocation, GIS systems, soil sampling and field analysis map generation, drones, autosteering and VRT. In precision planting [38], the seeding is done using a very fine predetermined inter plant distance, and robots with lasers are used for automatic weed zapping. Farm devices in the field are aligned automatically with robovator technology. With GPS, it has become possible to divide a farm into different zones based on the field conditions [160]. Variable rate fertilizer application [2,78,95] is also important for crop yield improvement. Wireless communications with drones also constitutes a major component of the IOUT connectivity. GreenStar Lightbar [15] is a tool from Deere & Co that is used to determine the location and width in the row crops. TK-GPS [57] is another device used to perform real time soil mapping.

The sensing technologies discussed in this section present many opportunities for advancing the state of precision agriculture through the IOUT. Availability of inexpensive sensors and their ability to communicate wireless enables their integrations to control systems in IOUT. Therefore, wireless communications, between heterogeneous equipment used in these sensor technology, has an important role in realization of the real-time decision making in IOUT. Moreover, adoption of sensor technology could be raised by a well-connected, reliable, and secure IOUT, and it will also help in development of improved sensing technologies in precision agriculture. Because, currently, the lack of availability of robust connectivity in the field is hindering rapid advancements in sensing technologies. Different approaches for wireless communications in IOUT are discussed in the next section.

5. Wireless connectivity

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

5.1. 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. For short-range communication and networking, license-free standards such as Bluetooth, ZigBee, and DASH7 are used in ISM bands. More

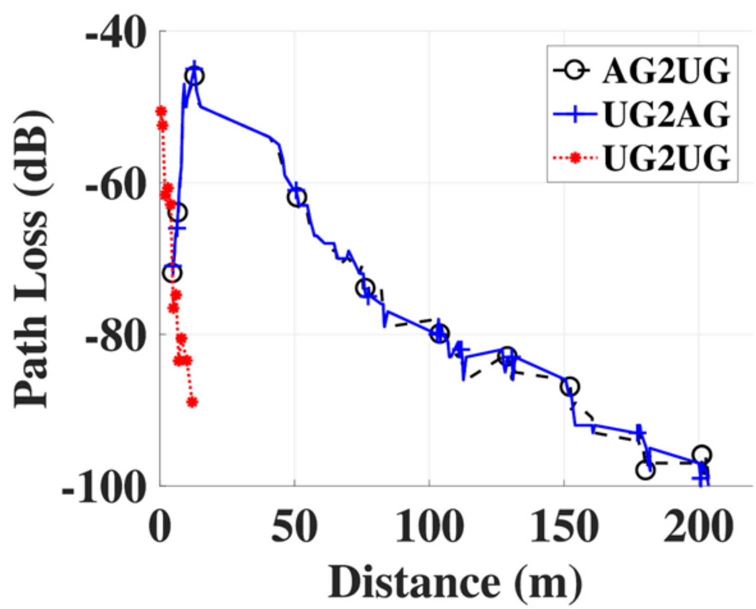

Fig. 4. Communication from soil.

recently, regulatory restrictions are relaxed by the FCC through new rules that allow the use of TV white space frequencies in farms [14] (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. In the following, we discuss in-field communications in detail.

UG communications: UG communication solutions enable complete concealment of UTs, which decrease operation costs and impacts from external elements [86]. 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 [86]. It can be observed that practical underground link distances are still limited to 12 m 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 impacts communication success in six main ways:

(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 [91]. Water holding capacity of each soil type is different because of its pore size. For example, lower water holding capacity of sandy soil leads to lower attenuation and high root mean square delay spread, whereas higher water holding capacities of silt loam and silty clay loam soils result in low root mean square delay spread and higher attenuation [133,134].

(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 variations. Soil dielectric spectra and its conductivity depends on the soil moisture. The relative dielectric constant range of dry soil is between 2 and 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 [147]. Coherence bandwidth of the underground channel is limited to a few hundred KHz range [129–131], 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 [129].

(4) Antennas in soil: When an antenna is buried, its return loss characteristics change due to the high permittivity of soil [85,151]. 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 path loss 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 [85].

(6) Lateral waves: For two UTs, wireless underground communication is conducted through three major paths: lateral, direct, and reflected (LDR) waves [86,130,133]. 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.

(7) Recent advances in wireless underground communications: Recent developments in wireless underground communications include the characterization of wireless UG channel and development of environment-aware, cross-layer communication solutions to achieve high data rate, long range communications with applications to precision agriculture. The impulse response of the wireless UG channel is captured and analyzed through extensive experiments [133].

With more than 1500 measurements in an underground greenhouse testbed, the effects of soil moisture and soil texture on wireless underground communication channel are analyzed. Through this analysis, the vital statistics of wireless UG channel impulse response (e.g., coherence bandwidth, root mean square delay spread, and power associated with multipath) are developed. The three main components of the UG channel, direct wave, reflected wave, and the lateral wave are validated. The coherence bandwidth of the UG channel has been shown to be less than 1.15 MHz which further decreases to 418 kHz for the distances greater than 12 m in soil [133]. Change in soil moisture also impacts the root mean square delay spread which requires moisture-based dynamic adaptation techniques in UG communications. The statistical model [134] is vital for tailored solutions for underground multi-carrier communication and soil moisture adaptive beam-forming.

Based on impulse response analysis, the multi-carrier modulation and wireless underground channel diversity reception schemes have been developed for the realization of high data rate communications [129]. The effects of soil type and moisture on the underground antenna, channel and system capacity are highlighted. Based on this analysis, multi-carrier modulation and wireless underground channel diversity reception schemes [131] have been developed. The optimum maximum ratio combining (MRCLDR) achieves the maximum gain. In this approach, three times SNR enhancement is achieved as compared to the SNR of a single antenna matched filter UG receiver. However, the interference from the reflected components is still present. Adaptive combining (AC-LDR) uses adaptive switching and selection process to suppresses undesired interference. Based on the proximity of the LDR receiver, either the D-wave or L-Wave component is dominant at the receiver. AC-LDR exploits this by adaptively switching and selecting the strongest lateral, or the direct wave. The R-Wave is not considered because it is the weakest component and results in performance degradation. In [131], the performance analysis of different modulation schemes through simulations and experiments has been carried out. The BER under equalization and diversity reception has been reported. A 3 times increase in SNR and improvement in BER from 10 −1 to 10 −5 are shown in wireless underground communication channel. Since use of sensing technologies in precision agriculture depend on reliable UG communications, these is a demand for high date rate, ubiquitous, reliable communications. These low error rate communication techniques help to achieve that goal in precision agriculture.

Moreover, based on UG antenna analysis, soil moisture adaptive beamforming (SMABF) using underground antenna arrays is also developed [130]. SMABF employs underground antenna arrays at the transmitter and omnidirectional antenna at the receiver. The lateral wave is maximized if the energy from the UG antenna is radiated in an optimum angle. In SMABF, beam steering is done to exploit the lateral wave in the underground communication by sending the energy in the optimum angle which maximizes lateral wave and leads to higher directivity. SMABF has complex array structures and needs phase shifters. With these advancements in UG communications, it has become possible to make progress from data collection to real-time processing and decision making in precision agriculture.

Magnetic induction (MI) and acoustic UG communications: Magnetic Induction (MI) based communications is another approach for UG communications. In magnetic induction [114,143], the rate of decay of received signal strength (RSS) is the inverse cube factor. Therefore, long range, high data rates signaling can not be done using MI, which is vital for IOUT paradigm. Moreover, the perpendicularity of transmitter and receiver coils (antennas) is a prohibiting factor to establish communications in MI. Wavelengths in MI communications tend to be large. Therefore, IOUT architecture can not scale with MI based UG communications in IOUT. Hence, because of these limiting factors, and due to in-feasibility of MI communications to establish communications with aboveground devices, MI based communications is not a reliable option for IOUT. EM-based UG communications are more suitable.

There are also some common characteristics in underwater communication [74] and UG communications. However, underwater communications can not utilize electromagnetic (EM) waves because of higher degradation of signals and water absorption. Therefore, other approaches (e.g., acoustic [74]) are used in underwater communications. Moreover, the acoustic approach is infeasible in IOUT UG communications because of vibration limitations.

Underground to UAV communications: The unmanned aerial vehicle (UAVs, also called drones) have recently emerged in the precision agriculture practices for sensing and communications of the filed conditions [123,148], agricultural surveillance using imaging [97], [83], and decision support [144]. Before the use of UAVs in precision agriculture, the satellite imagery was obtained for the purpose of monitoring. Through the use of UAV imaging, a detailed soil moisture map of the field can be produced in timely and inexpensive manner. Moreover, the crop growth can also be monitored by using UAVs and accordingly vegetation index is generated. The seed planting and pesticide applications are other important applications of UAVs in precision agriculture. The UAVs, when integrated with the IOUT in the field, will require reliable communications with sensors and radio equipment for real-time decision making. There are many challenges from UG to UAV communications (e.g., restrictions on UAV communications payloads and antennas, limited flight times, low communication range from the UG to UAV link, and specific operator skills and licenses required for UAV operation). Technology and regulatory advances in these areas will lead to enhanced integration of UAVs in precision agriculture IOUT.

Low power wide area networks (LPWAN): Since IOUT is designed for prolonged operation in the agricultural field, energy conservation plays important role in long term functionality and connectivity. Low Power Wide Area Networks (LPWAN) are designed not only to achieve energy conservation objective but also to attain long-range connectivity [122]. Due to this, LPWAN is suitable for IOUT communications where high data rate operations are not required and low latency of data transfer can be accepted for some applications. According to LPWAN Technical Workgroup, it has capacity to work over the time span of many years and is specifically designed for applications which need to transmit small packets intermittently. A brief overview of LPWAN technologies is given in the following:

(1) LoRa: Approaches designed to conserve energy like Long Range Wide Area Network (LoRaWAN) favor one-hop star topology where end-devices transmit small packets of information (0.290– 50 kbps) over long distances (up to 45 km in rural areas) [80]. This is more suitable for battery powered devices. Reliable communication over long distance is possible because of techniques like adaptive data rate, LoRa's chord spread spectrum radio modulation scheme, and gateways that decode data received on multiple channels modulated with different spreading factors [111]. However, since LoRa uses unlicensed frequency, the channel utilization is limited to 30 seconds per day by regulations. For application that requires a QoS level, the download channel increase the probability of collisions [81]. In precision agriculture, LoRa technology provides low-cost low-power communication solution for prolonged monitoring operations [29].

(2) Sigfox: Sigfox [44] is the first LPWAN technology and highly efficient in spectrum usage. It uses ultra narrow band (UNB) modulation. The communication range of Sigfox is up to 45 km and 12 km in rural and urban

areas respectively. Sigfox supports data rates of up to 250 kbps, and also uses unlicensed spectrum (868 MHz and 902 MHz) for communications. Consequently, the amount of data that can be transferred daily is also limited by regulations [161]. Sigfox provides many opportunities in precision agriculture IOUT to support connectivity among field equipment and UT sensors [45].

(3) On-Ramp/Ingenu: On-Ramp developed the IEEE 802.15.4k [20] technical standard for LWPAN. It only specifies the physical and MAC layer, and upper layers are complimented by other standards which operates at the upper layers. It uses higher bandwidth (1 MHz) as compared to other LWPAN technologies. IEEE 802.15.4k uses 902–928 MHz unlicensed spectrum. Its communication range is up to 15 km. Hence, it more suitable for communications agricultural forms spanning over large geographical areas [35].

(4) NB-IoT: NB-IoT [154] is a new physical layer standard by 3GPP LTE (Release 13). It can coexist with LTE and GSM. NB-IoT also uses narrowband signal and is meant for low data rate applications. It only uses 180 KHz of its 200 KHz bandwidth. NB-IoT operates in licensed spectrum and uses same band as of LTE. It supports standalone operation, broadband operation, and in-band operation. NB-IoT is also being used in many commercial agricultural solutions in Europe [32]. It also facilitates low-cost, long range, and prolonged battery life solutions in precision agriculture.

(5) Extended coverage GSM IoT: EC-GSM-IoT [12] is another low power long range LWPAN standard based on software update to cellular eGPRS. It can also co-exist with other mobile networks and designed to support battery life of up to 10 years. It operates in 800 MHz to 900 MHz and 1800 to 1900 MHz GSM bands. Many features of EC-GSM-IoT (e.g., inexpensive equipment, long range and coverage) makes it suitable for IOUT communication in precision agriculture. NWave [33], Platanus [36], Weightless [64], and Ingenu [20] are other major notable LPWAN technologies, which can be used for IOUT communications depending on the deployment, application, energy requirement, and equipment. These are also being used in precision agriculture connected vineyards [11].

Wireless PAN/LAN: Wireless PAN/LAN is also important for communications between farm machinery and equipment, field workers and central base stations in the field. Use of Wireless LAN/PAN enables high data rate, low latency communication in IOUT, which are not supported by LPWAN. Wireless PAN/LAN include many technologies such as Bluetooth, ZigBee, Thread, and Wi-Fi. In the following we present brief overview of these technologies:

(1) Bluetooth: Bluetooth [5] is standardized by Special Interest Group (SIG). Communication can be done up to 100 m distances and it uses frequency hopping spread spectrum technique. Bluetooth Smart is the low energy version and can operate in broadcast and connected mode. Bluetooth uses 2.4 GHz ISM band and has bandwidth up to 25 MHz. It is also being used in development of a low energy moisture- and temperature sensor intended for use in an agricultural wireless sensor network system [76].

(2) ZigBee: ZigBee [65] operates on the top of 802.15.4 MAC/PHY and it consists of application and network layer protocols. It can operate in a star and mesh topology with bandwidth up to 1 MHz and communication range of up to 10 to 30 meters. A smart agriculture system by using ZigBee technology has been developed in [117].

(3) Thread: Thread [56], self-healing mesh network protocol, functions on IEEE 802.15.4 MAC/PHY and is simple and secure battery friendly LAN protocol. It can supports up to 250 devices and provides security at network and application layers.

(4) Wi-Fi: IEEE 802.11 [19] is high data rate communication standard with support for data rates higher than 1 Gbps. It has physical layer standards for different ISM bands (2.4 GHz, 5 GHz and 60 GHz) and used different channel bandwidth up to 160 MHz. A remote monitoring system using WiFi, where the wireless sensor nodes are based on WSN802G modules, has been developed in [119].

Cellular technology in IOUT: As more and more IOUT applications are being developed, the demand for cellular and broadband connectivity IOUT solutions is reaching at critical levels. Lack of broadband cellular communication in rural areas is a major challenge as it hinders instant access to big data being generated from the field. Currently, data has to be collected and transmitted manually from the deployed IOUT systems which is major bottleneck in adoption of precision agriculture practices in remote rural areas. One main factor for non-existent or slow cellular data communication speeds is the huge expenditure on commissioning of required infrastructure rural communities. There are also many system and cost related challenges in Machine-to-Machine (M2M) cellular communications [70] as main purpose of cellular design was human communications. However, a recent release of LTE cellular standard has the support for M2M communications and can be used for communication in production fields being served with LTE networks. However, IOUT devices are required to be compatible with the cellular standard and energy consumption challenges restricts their use in battery powered devices for prolonged duration. To overcome these challenges, low power devices can be connected through in-field communications and subsequently data can be collected and transmitted to the cloud by using externally powered gateways with cellular capabilities.

Energy consumption in IOUT: In IOUT, energy consumption is a vital issue because of the low power requirement for sensors in order to operate for prolonged periods without battery replacement. Moreover, the channel quality in UG communications is impacted by physical parameters of the soil (e.g., soil moisture).

In [84], a connectivity model of IOUT for different soil physical parameters has been developed by designing the cluster size distribution under sub-critical constraints. A novel aboveground communication coverage model for underground clusters has been developed. To maintain connectivity while reducing energy consumption the transmit power control and environment aware routing are proposed. It is shown that these approaches can maintain network connectivity under all soil moisture conditions while reducing energy consumption. Moreover, it has also been shown that use of relaying nodes based on soil wetness conditions can further decrease the energy consumption.

5.2. Cloud and big data in precision agriculture

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 [157]. There are online marketplaces where big data sets and agricultural apps are used to analyze a region and make decisions to maximize crop yield [136]. Additionally, in-situ SM sensors can be linked to national soil moisture databases for complete, accurate, and comprehensive information of soil moisture [27,46,48,4 9,53,60,63]. With the support of cloud services, real-time visualization and decision support can be provided. Therefore, Cloud can be used as a hub of data storage and processing applications in precision agricultural. Moreover, Cloud allows the scalability of IOUT paradigm from the field level to bigger geographic areas by forming network of farms.

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. The integration of IOUT with creates new avenues to form robust stakeholders in precision agriculture such as growers, industry, and trading companies and would results in increased efficiency and sustainability of whole precision agriculture ecosystem. In addition to integration of farm equipment data to soil and weather databases, other examples include linking UAVs and robotics to precision agriculture paradigm.

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 connect 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. Moreover, there is a need of development of standardized interfaces for seamless connectivity and collaboration between different components of the precision agriculture ecosystem.

The IOUT paradigm enables sensing and communications of even minor changes in the field including change in physical properties of the soil and growth of plants. Major sources of big data in precision agriculture are ESA satellite images, NDVI from drones, user maps (yield, electrical conductivity, and others), and soil data. This process generates big data and it becomes very important to extract meaningful information from this huge amount of data. This is also crucial for real-time end user decision making and in evaluation of return on investment. Therefore, it is necessary to develop big data analytics in precision agriculture [156]. It is also essential to analyze the reduction in input cost in water resources, energy consumption and labor cost by adopting precision agriculture practices [73]. Other examples of the big data analytics in precision agriculture are factors affecting crop yield; and demarcation of field zones based on particular application such as productivity, soil moisture, nutrients, harvesting. Farmers, as the biggest stakeholder in the precision agriculture, need to use the technology to see the potential benefits with out being overloaded with the data. Therefore, the big data analytics to show increase in crop yield and improvement in overall production efficiencies, which can deliver tangible benefits, are vital for success of the whole precision agriculture ecosystem.

6. An overview of IOUT enabling technologies and testbeds

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

6.1. Academic IOUT systems

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 [86].

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 [100]. In this testbed, a mobile sink is installed on one of the controller towers of the center pivot irrigation system [86]. The current configuration includes two antennas facing opposite directions allowing the reception of data from nodes at a distance of 150 m–200 m. A solar panel provides sustainable energy in the field. 10–16 buried 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 ft. 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. This field testbed is fully functional system developed to investigate IOUT sensing and communications capabilities in an agriculture field using center pivot irrigation, sensors, aboveground and underground communication devices.

An indoor testbed has been designed and developed inside the greenhouse which supports dynamic soil moisture control for wireless underground communication experiments [133]. The testbed is made of 100 in. long, 36 in. wide and 48 in. 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, a testbed based on magnetic induction (MI) underground communications has been developed in [143]. 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. SoilBED [89], is another underground testbed developed for cross-well radar experiments in soil. It is used for investigation of EM wave propagation and for detection

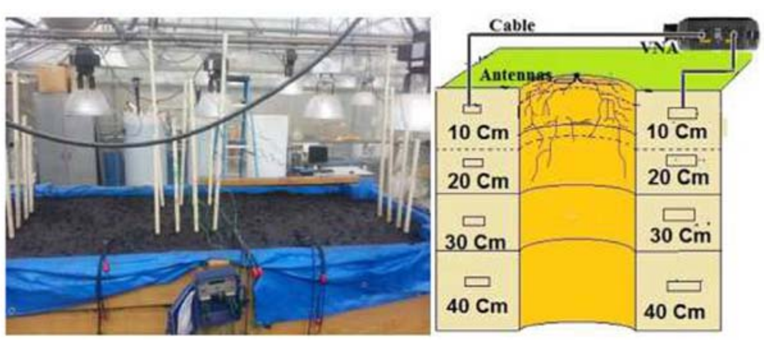

Fig. 5. The indoor testbed [133].

of presence of contaminated materials in soil. SoilBED can also be used for underground channel and antenna characterization, and empirical validations of underground communication channel models.

Thoreau [161] is an IOUT testbed on an university campus that collects and curates time and geo-tagged data on an open platform on the cloud. It is based on Sigfox design and operates in the 900 MHz unlicensed bands with frequency hopped and narrowband operation. It has very low data rates and soil properties including soil temperature, soil moisture, electric conductivity, and water potential are measured.

Another precision agriculture testbed has been developed for real-time sensing in the field [79]. It is used to sense related soil properties for real-time decision making. BioSense [4] Institute is an R&D institute for IT in biosystems. To achieve their vision on the future of agriculture and food production, BioSense works on the areas of machinery auto-steering and automation, EC probe & XRF scanner, electrical conductivity map, normalized difference vegetation index (NDVI) map, yield map, remote sensing, nano and micro-electronic sensors, big data, and Internet of things aimed to food production. BioSense Institute, supported by University of Novi Sad, Serbia, focuses on the design development of advanced ICT solutions in agriculture, food, ecology, environmental protection, and forestry. Research results of BioSense Institute are helping European countries and regions to improve agricultural and environmental standards. It is also working in nano and microelectronics, communications and signal processing, remote sensing and GIS, robotics and mechatronics, knowledge discovery, and BIO-related research fields such as agriculture, ecology, environmental sciences, and forestry. It consists of many researchers from various fields labs from Europe. Their solution for Big Data is AgroSense [3], an agricultural platform which store and present information to farmers, agri-companies, government, banks, and insurance companies aimed toward improving crop yield while reducing costs.

Internet of Food and Farm (IoF2020) [22] is an European project that has 19 use cases in 5 agri-food production sectors: arables, fruits, vegetables, dairy, and meat. An example in arable is the combination of data from sensor networks for smart wheat management with crop models and other data sources (e.g., disease, crop stage detection, cultivar characterization from phenotyping, and others) to generate high spatial-temporal resolution and to develop new models. In fruits, a fresh table grapes chain project uses information from weather station and wired sensor (soil moisture, soil temperature, electrical conductivity, and leaf wetness) for disease forecasting and to control irrigation using flow meters and solenoid valves. Solar powered data loggers transmit the data using GPRS network. A case study in vegetable is the tracking of greenhouse tomato-crops chain by setting the optimum ambient conditions to reduce the usage of resources (e.g., pesticide application could be avoided completely) and increase energy efficiency. In dairy, 15 grazing cows are tracked on the pasture and inside the dairy barn using three beacons. A case in meat is the tracking of pigs using RFID tags, which reduces boar taint, health problems, and improve productivity. Sensor are also used for climate monitoring, register weight gain, feeding and drinking patterns, and food and water consumption.

A ZigBee based IOUT has been developed in [158] with application in precision agriculture. Related soil properties such as humidity and pH are sensed using this architecture. An IOUT for soil moisture sensing at multiple depths has been developed in [125]. It consists of wireless communications nodes, sensors, data transfer gateways, and web modules for real time sensing, communication, and visualization in the field. An IOUT testbed for snow and soil moisture monitoring has been developed in Sierra Nevada, California [103]. With 300 sensors spanning over an area of multiple kilometers, this IOUT sensing testbed is used to record measurements of soil water content, snow depth, matric potential, and other related parameters; and a detailed sensing, and communication performance analysis data is also reported. A summary of the existing academic architectures is provided in Table 1.

6.2. Commercial IOUT solutions

In most commercial products, OTA wireless communication is utilized, where the UT includes a variety of high-end sensors that measure properties like soil moisture, temperature, and electrical conductivity. Consequently, measurements generally represent a single point in the field. UT's can interconnect to create a communication mesh, but in most cases, they are connected directly to a tower in the field with cellular or satellite communication capabilities. If the UT is not buried underground, redeployment of the equipment is needed after planting and before harvesting in each growing season to avoid damages to the equipment by the farming machinery. A classification of the commercial IOUT solutions, companies, and their products are presented in Fig. 6. Modularity in the design of IOUT devices is highly desirable as the requirements can change over time and are tailored for a specific application. For example, the transmission range influence the selection of a protocol and the transceiver that can meet the communication demands. Solutions could be customized for a specific application and ordered as a complete solution, so they will work out-of-the box. There are companies that specialize in agricultural solutions. In other cases, the architecture is required to be more specific and fast prototyping using OEM components is more appropriate. Once data is collected, end-users need networks to transmit the data, servers for storage and processing, and cloud-based applications to display the information. A summary of the commercial solutions

Table 1. Academic IOUT systems.

Architecture	*Sensors*	*Comm. Tech.*	*Node Density*
Automated Irrigation System [96]	DS1822 (temperature) VH400 (soil moisture)	OTA, ZigBee (ISM)	One node per indoor bed
Soil Scout [145]	TMP122 (temperature) EC-5 (soil moisture)	UG, Custom (ISM)	Eleven scouts on field and a control node
Remote Sensing and Irrigation Sys. [105]	TMP107 (temperature) CS616 (soil moisture) CR10 data logger	OTA, Bluetooth (ISM)	Five field sensing, one weather station
Autonomous Precision Agriculture [86]	Watermark 200SS-15 (soil moisture) Data logger	UG, Custom (ISM)	Up to 20 nodes per field
SoilNet [77]	ECHO TE (soil moisture) EC20 TE (soil conductivity)	OTA, ZigBee (ISM)	150 nodes covering 27 ha
MOLES [143]	Magnetic Induction Communications	Magnetic Induction	Indoor Testbed
Irrigation Nodes in Vineyards [62]	Yield NDVI	Variable Rate Irrigation	140 irrigation nodes per field
Sensor Network for Irrigation Scheduling [43,82]	Capacitance (soil moisture) Watermark soil moisture sensors	OTA	6 nodes per acre
Cornell's Digital Agriculture [7]	E-Synch, Touch-sensitive soft robots Vineyard mapping technology, RTK	OTA	Field Dependent
Plant Water Status Network [126]	Crop water stress index (CWSI) Modified water stress index (MCWSI)	OTA	Two management zone - Two treatments in each zone
Real-Time Leaf Temperature Monitor System [28]	Leaf temperature Ambient temperature Relative humidity and Incident Solar radiation	OTA	Soil and plant water status monitors
Thoreau [161]	Temperature, Soil moisture Electric conductivity and Water potential,	OTA	Based on Sigfox
FarmBeats [149]	Temperature, Soil moisture Orthomosaic and pH,	OTA	Field size of 100 acres
Video-surveillance and Data-monitoring WUSN [93]	Agriculture data monitoring Motion detection, Camera sensor	OTA	In the order of several kilometers
Purdue University's Digital Agriculture Initiative [40]	Adaptive weather tower PhenoRover sensor vehicle	OTA	Field Dependent
Pervasive Wireless Sensor Network [155]	Soil Moisture, Camera	OTA	Field Dependent
Pilot Sensor Network [109]	Sensirion SHT75	OTA	100 nodes in a field
SoilBED [89]	Contamination detection	UG	Cross-Well Radar

is provided in Table 2. Major classes of the commercial solutions are highlighted in the following.

- *Agricultural solutions.* John Deere's Field Connect uses 3G connections to transmit information from eight sensor probes located a mile away (three if satellite communication is used) that measure soil moisture at various depth, temperature, humidity, wind speed and direction, rain, and leaf wetness. MimosaTEK provides irrigation and fertigation solutions scaled to small, medium, and large farms [31]. TempuTech [55] provide wireless solutions to monitor temperature and humidity in grain elevators. Microsoft is developing FarmBeats which is an AI & IoT based platform for Agriculture [13]. These commercial agricultural solutions provide full support in precision agriculture including sensing, communications, and the cloud.

- *Out-of-the-box packages.* Smartrek Technologies develops wireless nodes for different types of sensors and gateways that can be set up easily into a network mesh [47]. Nodes are protected by weatherproof enclosures which is a requirement for farm outdoor setting. Accessible ports allows the installation of third-party soil moisture sensors and weather detection. Libelium has developed a Plug & Sense Smart Agriculture solution [37] for temperature and humidity sensing, rainfall, wind speed and direction,

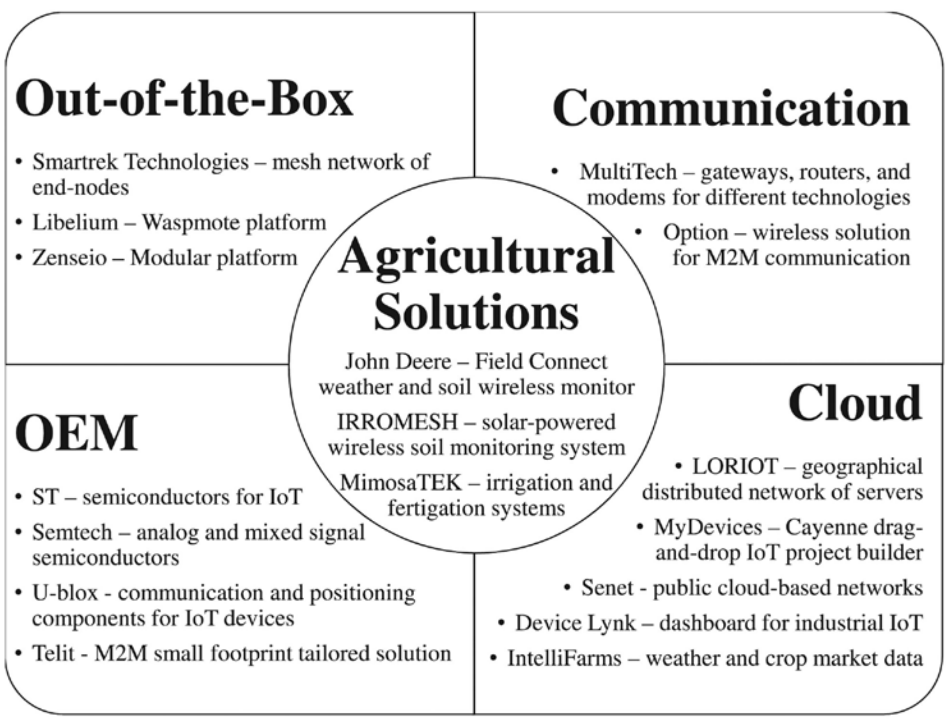

Fig. 6. The classification of commercial IOUT solutions.

Table 2. Commercial IOUT systems.

Architecture	*Sensors*	*Comm. Tech.*	*Node Density*
IRROmesh [24]	200TS (temperature) Watermark 200SS-15 (soil moisture)	OTA, Custom (ISM) OTA, Cellular	Up to 20 nodes network mesh
Field Connect [26]	Leaf wetness Temperature probe Pyranometer Rain gauge Weather station	OTA, Proprietary OTA, Cellular OTA, Satellite	Up to eight nodes per gateway
SapIP Wireless Mesh Network [10]	Plant water use Measure plant stress Soil moisture profile Weather and ET	OTA	Up to 25 SapIP nodes with 2 sap flow sensors each.
Automated Irrigation Advisor [58]	Tule Actual ET sensor	OTA	Field Dependent
Internet of Agriculture-BioSense [4]	Machinery auto-steering and automation EC probe & XRF scanner Electrical conductivity map NDVI map Yield map Remote sensing Nano and micro-electronic sensors Big data, and Internet of things	OTA	Field Dependent - Real-time irrigation decision making,
EZ-Farm [18]	Water Usage Big data, and Internet of Things Terrain, Soil, Weather Genetics Satellite info Sales	OTA	IBM Bluemix and IBM IoT Foundation
Internet of Food and Farm (IoF2020) [22]	Soil moisture Soil temperature Electrical conductivity and Leaf wetness	OTA	Field Dependent
Cropx Soil Monitoring System [8]	Soil moisture Soil temperature and EC	OTA	Field Dependent
Plug & Sense Smart Agriculture [37]	Temperature and humidity sensing, Rainfall, Wind speed and direction, Atmospheric pressure, Soil water content, and Leaf wetness	OTA	Field Dependent
Grain Monitor-TempuTech [55]	Grain temperature and Humidity	OTA	Multiple Depths in Grain Elevator
365FarmNet [1]	Mobile device visualization tool for IOUT data	OTA	Field Dependent
SeNet [42]	Sensing and control architecture	OTA	Field Dependent
PrecisionHawk [39]	Drones for sensing Field map generation	OTA	Field Dependent
HereLab [16]	Soil moisture, Drip line psi and rain	OTA	Field Dependent
IntelliFarms [21]	YieldFax Biological BinManager	OTA	Field Dependent
IoT Sensor Platform [23]	IoT/M2M sensors	OTA	Field Dependent
Symphony Link [52]	Long Range Communications	OTA	Field Dependent

atmospheric pressure, soil water content, and leaf wetness. Libelium provides platforms and end-user devices that encompass communications standards such as LoRaWAN, LoRa, Sigfox, sub GHz, ZigBee, DigiMesh, WiFi, RFID, NFC, Bluetooth/BLE, 3G, 4G, and GPRS. Sensor boards can be connected to their Waspmote platform to attach 120 different sensors. Libelium also hosts an IoT marketplace and provides cloud services to manage IoT devices and online programming. Cropx's [8] IOUT consists of hardware and software components used to measure soil moisture, temperature, and EC for real time irrigation decision making. PrecisionHawk has developed an IOUT platform [39] using drones, which is used for sensing and field map generation. It supports visual imaging, thermal and multi-spectral imaging for field map generation in precision agriculture. These out-of-the-box packages are important component of the precision agriculture to support different types of applications.

- *OEM components.* OEM components are commonly used in the manufacturing of nodes at a large scale. However, the prototyping or small scale production of very specific UT will also required the selection of OEM devices. ST [51] develops internal components for IoT devices like accelerometers, gyroscope, and MEMS microphones. Semtech Corporation is a supplier of high-performance semiconductors and advanced algorithms [41]. U-blox specialized in communication and positioning components for IoT devices [59]. Telit is an M2M solutions company with focus in IoT development [54]. Telit provides tailored hardware and software solutions in small size modules. Products can transmit data using cellular, Bluetooth/ BLE, LoRa, Low Power Wide Area (LPWA), Positioning, Sig- Fox, Sub GHz, Wi-Fi, and M-Bus wireless technology. Herelab provides proof of concept deployment and rapid prototyping service of IoT custom platforms [16]. For instance, in agriculture, sensor interfaces can be rapidly attached to a template, and the corresponding instructions can be adapted from the code library. Herelab also organizes labs and workshop to introduce new tools and promote the usage of IoT devices. These components serve as useful building blocks of IOUT sensing and communications paradigm.

- *Cloud-based services.* Cloud service allows worldwide access to the information collected by IOUT devices without any previous web programming knowledge. Farmers and other professionals do not need to spend time to hire another party in order to configure a server to make use of the data collected; and can take decision right away. LORIoT provides cloud services on a geographical distributed low latency network of servers where users connect their LoRaWan gateways. Among the web services they offer are the management of devices, cloud storage of data, safeguard of encryption keys, and LoRaWan to IP/IPv6 translation [30]. MyDevices offers IoT developers services to promote their solutions. One attractive feature of MyDevices is that it offers Cayenne, a drag-and-drop IoT project builder. End users can create an account and use Cayenne web and mobile applications to register their IoT devices and instantly display sensed data on a fully customizable dashboard [6]. Senet operates two public cloud-based networks, Managed Network Services for IoT (MNSi) and Low Power Wide Area Virtual Network (LVN), that provide secure, efficient, and scalable connectivity to low-powered devices [42]. A proprietary network operating system handles end-devices messages and LoRaWAN gateways, generation of keys for encryption, decryption of messages, and hosting the portal for device management, among other activities. Device Lynk offers an online dashboard for data visualization of data captured using IoT industrial devices [9]. Intelli-Farms provides diverse agricultural solutions such as reporting weather conditions, providing market crop pricing, and monitoring storage conditions in silos and bins. It also host the Intelli-Farms platform where customer can get access to all their solutions in a centralized fashion [21]. 365FarmNet platform [1] is an agricultural data management service that is currently offering free field mapping for precision agriculture. Research challenges in IOUT are presented in next section.

7. Research challenges

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

1. Due to large area of deployment in agricultural fields, low cost and low complexity IOUT devices are desirable with ability to sustain rough terrains in all type of soil moisture regimes.
2. 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.
3. Due to availability of different types of SM sensors, their integration with communication equipment is a major challenge. A standard protocol is required for seamless integration of different types of sensors to the communication devices in IOUT.
4. 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.
5. Advanced security mechanisms are required to protect information transfer in the fields. Moreover, field-based privacy solutions are required such

that information from multiple fields can be fused for more accurate decisions while preserving the privacy of growers.

6. Seasonal changes and crop growth cycles need to be considered as they temporarily alter the conditions in which the equipment typically works. Freezing temperature affects power consumption, but equipment can be set to deep sleep as monitoring might not be necessary. The beginning of the growing season or a crop rotation can introduce heavier equipment on the field and UTs need to be buried deep enough to avoid damages.
7. Due to dynamic changes in the communication medium in soil, UTs should be able to autonomously 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 [86,129–131,133]. Impacts of soil physical properties, soil moisture on UG communication should be modeled. A detailed insight into these effects will help to realize a reliable, scalable IOUT architecture.
8. Impacts of soil physical properties, soil moisture on UG communication should be modeled. A detailed insight into these effects will help to realize a reliable, scalable IOUT architecture.
9. Specialized link-layer and network layers protocols are needed for UG communications for scalable, reliable, and robust data transfer in IOUT.

8. Conclusions

We introduced the Internet of Underground Things (IOUT) for real-time decision making in agricultural fields. A complete architectures for precision agriculture based IOUT has been presented. It has been shown that the sensing and communications are the main component of the IOUT. A detailed overview of sensing and communication technologies including academic and commercial solutions is presented. In-field communications (UG, LPWAN, LAN, cellular) and cloud are discussed in detail. Challenges to the realization of IOUT are highlighted, and testbed designs for IOUT realization are presented. Recent advances in the theory and applications of wireless UG communication are also reported.

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