8-17-2020

Current Advances in Internet of Underground Things

Abdul Salam
Purdue University, salama@purdue.edu

Usman Raza
Purdue University

Chapter 10
Current Advances in Internet of Underground Things

Abstract The latest developments in Internet of Underground Things are covered in this chapter. First, the IOUT Architecture is discussed followed by the explanation of the challenges being faced in this paradigm. Moreover, a comprehensive coverage of the di erent IOUT components is presented that includes communications, sensing, and system integration with the cloud. An in-depth coverage of the applications of the IOUT in various disciplines is also surveyed. These applications includes areas such as decision agriculture, pipeline monitoring, border control, and oil wells.

10.1 Introduction

Internet of Underground Things (IOUTs) is subset of IoT which consists of sensors and communication devices for real-time sensing and monitoring of soil. IOUT di ers from IoT in that the sensors and communication devices are either partly or fully buried underground. IOUT extends Wireless Underground Sensor Networks (WUSNs) [52], [58], [61], [9], [75], [77], [81], [86], [100], [139], [141], [145], [157], [158], [61], [164], [104], [168], [67], [72] and include autonomous devices which collects the required and relevant earth information. These devices are connected via some communication and network systems which sends information out from the field to farmers and growers for decision making. IOUT, through Internet, facilitates seamless access to agriculture information. IOUT operation includes: in-situ soil sensing such as soil's moisture, temperature and salinity etc, communication through soil and plants, and real-time environment information, e.g., rain, wind and solar etc. IOUT aims to improve and provide efficient food production mechanism. It achieves complete autonomy by connecting with the various farming equipment such as seeders, combines and irrigation systems [45]. The operating environment of IOUT is very unique, i.e., access of information from soil, communication through plants and soil, exposure to element and unexpected environmental conditions. Existing over-the-air (OTA) wireless solutions were not made for such environment, therefore, these OTA solutions face significant performance challenges in IOUT environment.

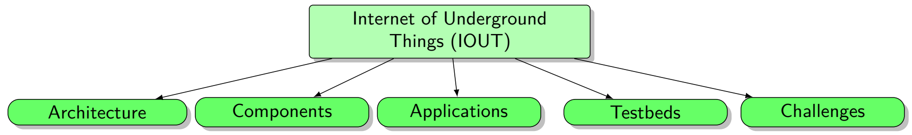


Fig. 10.1: Organization of the Chapter

In attempt to deal with challenges of communicating in IOUT environment, a new type of wireless communication is proposed: wireless underground communications (UG) communications [52, 177],. Wireless UG communications is a communication method where radios are buried under earth and communicate through soil. IOUT along with the UG communication will be beneficial in conserving water and improving crop yields [168], [104]. Advancement in IOUT technologies can also improve operations of various applications (underground mining, pipeline assessment and landslide monitoring) which utilizes earth underground resources [54], [9], [139], [145], [177], [29].

10.2 IOUT Architecture

As mentioned in previous section, IOUT consist on interconnected heterogeneous nodes customized for field operations. IOUT is expected to provide following functionalities:

10.2.1 Functionalities

- *In-situ Sensing*: In-situ sensing refers to a buried sensor collecting the information (soil moisture, salinity and temperature) from the soil. In-situ sensing plays a very important role in gathering precise localized information of the soil. These sensors can be used in two ways: 1) they can be integrated on the chip with components in the architecture, 2) can be used as standalone separate sensors connected to the main components through wires [36, 53].
- *Wireless Communication in Challenging Environment:* Communication systems in IOUT are either deployed in the field or within the soil. As these systems are exposed to natural environment, they should sustain the unexpected rough and challenging environment. OTA solutions should be customized to changing environment because of irrigation and growth of the crop. UG solutions are shielded from the environment and should be able to communicate through the soil and adapt to dynamic changes in soil parameters.

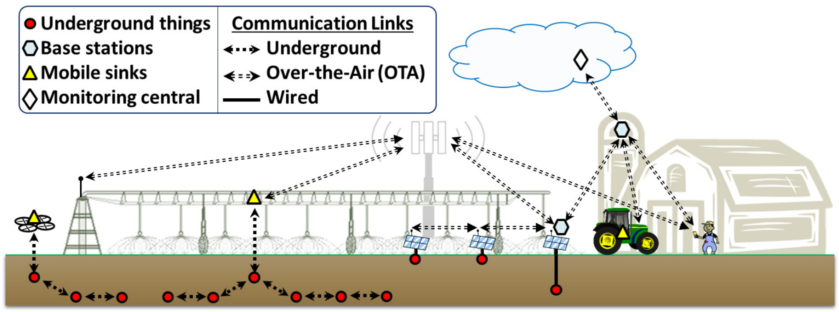


Fig. 10.2: IOUT Paradigm in Precision Agriculture [111]

- *Inter-Connection of Field Machinery, Sensors, Radios, and Cloud:* IOUT systems are mainly responsible for collecting data from the field and sending it to the cloud for further processing and decision making. It uses a multitude of diverse devices for successfully completing these operations. IOUT should be able to seamlessly integrate and link these large number of di erent devices. In addition to collection of information, IOUT must also be able to automate the field operations based on this information.

Fig. 10.2 illustrates the IOUT architecture which aims to achieve these required functionalities. The components of this architecture are described below:

10.2.2 Elements

- *Underground Things (UTs):* An UT is an embedded system with on board sensing and communication component. UTs can either partially or fully buried in the ground. UTs are protected from the environment with water proof enclosure and watertight containers. Buried UTs are protected from the farm's equipment. Soil temperature and moisture sensors are used most commonly, however, many other soil- and weather- related phenomena can also be monitored. Bluetooth, satellite, ZigBee, underground and cellular are some of the existing communication schemes. Bluetooth [71, 86] and underground wireless [9, 47] provide short range communication of about 100 meters. Commercial products operating in industrial, scientific and medical (ISM) band covers three times larger distance of short-range communication systems. Cellular and satellite communication systems provide much longer range covering more distance. For large field size, a network can be configured to send the data to a collector sink and self-heal if nodes are unreachable. Nodes are powered by the combination of batteries and solar panels. UTs are cheaper as they are deployed in a very large number [51, 77].

- *Base Stations:* Base stations are used as gateways for transferring data from the field to the cloud. They are permanent structures and are installed in buildings, e.g., weather station. Due to high power of processing and communication capabilities, base stations are expensive and well protected [77].
- *Mobile Sinks:* Mobile sinks are attached with the moving farming equipment such as tractors or irrigation systems [9, 52]. However, sometimes turning the farming equipment just for data retrieval can sometimes be expensive. Hence, as an alternative, unmanned vehicle (ground robots or quadrotors) are also being used for such purposes.
- *Cloud:* The purpose of the cloud services in IOUT architecture is to provide permanent storage for information, real-time processing of information, decision making and integration with other databases such as soil and weather.

Table 1.1 and Table 1.2 provides the summary of existing academic and commercial architecture. Most of the commercial solutions uses OTA communication systems where UT connects to field tower via cellular or satellite communication. This diverse communication architecture makes it difficult to form a unified IOUT architecture fulfilling all the requirements. Lack of standard sensing and communication protocols makes this task more difficult.

10.3 IOUT Components

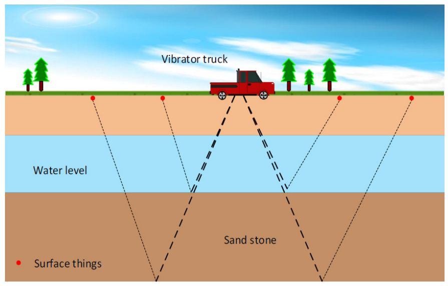
10.3.1 Communications

This section explores some communication systems which can be used in the implementation of IOUT systems. Here, all these systems are discussed at very basic level. There are di erent technologies that can be used for communication in IOUT. The wired IOUT solutions uses coaxial cables and fiber optics. Wired solutions provide high data rates and are being used in di erent applications [55, 80, 155]. Although, these wired solutions provides reliable and accurate communication, however, they increase the complexity and poses scalability issues. Given the disadvantages of wired systems, wireless solutions are termed as feasible solutions to provide relatively low complexity and scalable solutions.

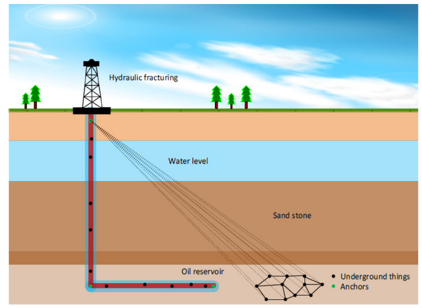
Wireless solutions are classified on the basis of technology they are using to transmit information. These solutions includes: Electromagnetic waves (EM), magnetic-induction (MI), acoustic waves and VLC. Acoustic wave are used for detection purposes, e.g., detecting objects in underground environment [103] and detecting water content in the soil. the disadvantage of using acoustic-based system is the low data rate and high noise and attenuation [73].

Some of the technologies and their feasibility for IOUT systems are given below:

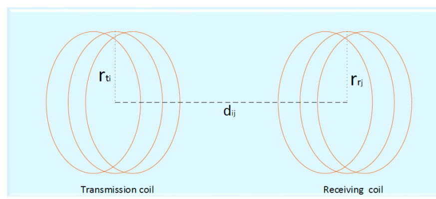
Magnetic induction (MI): Magnetic Induction-based IOUT communication network consist of buried sensors (UTs) and above-ground (AG) devices. Above-ground devices can provide extended communication by using extra large and



(a)



(b)



(c)

Fig. 10.3: Communication Technologies in IOUT: (a) Acoustic-based IoUT, (b) EM-based IoUT, (c) Schematic of MI communication link [114]

powerful dipole antenna. Therefore, downlink communication (AG2UG) is single-hop and upstream (UG2AG) is multi-hop due to limited transmission power [41].

MI transceiver is composed of induction coils producing magnetic fields. these magnetic fields can be sensed by nearby coil. Each induction coil is attached to a capacitor in a way that it operates at resonant frequency. In an attempt to achieve long transmission range (10 to 100 m) in IOUT moderate size coils are preferred. A time-varying magnetic field is produced by the coil of transmitter node which in turn induces current at receiver antenna. This procedure is shown in Fig. 10.3(c)

Decay rate of received signal strength (RSS) is the inverse cube factor in MI. Hence, high data rates and long-range is not an option in MI-based systems and both are primal requirements of IOUT. In MI, transmitter and receiver antenna are perpendicular to each other which prevents establishing communication in MI. Therefore, MI-based IOUT architecture are not scalable. Owing to these factors and inability to communicate with above-ground devices, MI-based systems are not a reliable option for IOUT systems and their performance is tried to improve by using relay coil [28, 92, 104, 166]

Acoustic: Acoustic waves have been used as communication and detection techniques in underground measurements. Geologist have been using to explore natural resources (oil and gas) by measuring the reflected acoustic waves from the ground. It has been used in drilling for communication with underground drilling equipment. Some of the major applications of acoustic waves include buried pipeline monitoring, earthquake monitoring, seismic exploration, smart drilling for oil and gas reservoirs. there exist many studies in the literature for acoustic which can also support other applications[40].

Acoustic methods can be active or passive depending on how signal is generated. Passive methods generates an acoustic signal, from the underground, after some major events like earthquake or volcanic explosion, or sudden underground changes such as structural transformation, pipeline leakage or rock crack formation. Sensors are placed in the vicinity of these events which detect infrasonic wave and helps in predicting such events. Active methods signal is self-generated by an artificial explosion/vibration which is sent underground to understand the earth's property (see Fig. 10.3(a)). Reflection-based seismology is one popular application of such method Though IOUT UG communication and underwater communication [163] have some similarities. However, they are not suitable choice for communication in IOUT because of low propagation speed and vibration limitations. Therefore, they are mostly used for the detection purposes.

Unmanned Aerial Vehicle (UAV): Unmanned Aerial Vehicle (UAV) has recently seen an advancement in IOUT precision agriculture for sensing the communication of the field conditions [96, 111], imaging surveillance [101] and decision support [110]. Before the popularity of UAVs, only purpose of the satellite imaging was used for only monitoring purposes, however, now its i being used to create soil moisture maps for the field in timely and cost-efficient methods. Other applications includes: crop growth monitoring, seed planting and pesticide applications.When integrated with IOUT systems, UAVs require efficient communication protocols to communicate with the sensors, radio antennas and make real-time decision. However there are some challenges face by the UG to UAVs communication e.g., limitation on payloads antennas used by UAVs, limitations on time of the flight, need of special skills for operating UAVs, operational license fro UAV and shorter communication range. Advancement in technology and regulatory restrictions can lead to improved integration of UAVs in IOUT Eco-system [37].

Electromagnetic Waves for IOUT: Electromagnetic (EM) waves have been extensively used for communications in various application of IOUT in agriculture [19, 187], seismic exploration [153], oil and gas (Fig. 10.3(b)), and drilling [51, 70, 84]

Low Power Wide Area Network (LPWAN)): IOUTs are designed to operate for a longer period of time which makes energy conservation a very important issue. Low Power Wide Area Network (LPWAN) not only conserve energy but also give long-range connectivity [42, 105]. LPWANs are used in those IOUT applications which have primary requirement of energy conservation and range, therefore, high data rate operations are not required and latency is acceptable. As per one of the LPWAN technical workgroup, LPWAN can operate for several years and customized to the applications which transmits small data packets intermittently. Some of the famous LPWAN technologies are: Long Range Wide Area Network (LoRaWAN) [59], Sigfox [17], NB-IoT [182] and Extended coverage GSM IoT (EC-GSM-IoT) [5].

Wireless PAN/LAN): One of the shortcoming of LPWAN is its low data rate. This shortcoming can be over come using wireless PAN/LAN. It can facilitate communication between machinery and equipment, base stations and field workers.

Wireless PAN/LAn include technologies like Bluetooth [1] provides bandwidth upto 25 MHz and range of 100m, ZigBee [31]] provides bandwidth up to 1 MHz and range of 20-30m , Thread [22] provides secure support for upto 250 devices and Wi-Fi provides single channel bandwidth upto 160 MHz[9, 38].

Cellular Technologies: With more advancement in IOUT applications, there is an increasing demand of cellular and broadband connectivity in IOUT solutions. There is a scarcity of cellular broadband in rural area is the major hurdle in accessing the big data being generated from the IOUT field. one of the reason of no or slower cellular communication speed, in rural area, is the cost of infrastructure. Currently, data is manually collected and transmitted to base stations. Cellular communications were designed for the human communications, therefore, Machine-to-Machine (M2M) communication faces system and cost related challenges. However, new LTE standards are coming with support for M2M communication but IOUT devices must be compatible and low-powered because of the energy constraints [39].

10.3.2 Sensing

Real-time sensing is one of the major functionality of IOUT architecture. Real-time sensing is the cause of widespread adoption of IOUT. It also gives efficiency in IOUT applications [33, 108]. Although a complete chapter in this book is dedicated to the sensing component of IOUT, however, for the sake of completion, some of the IOUT sensing technologies are discussed very briefly in this section.

IOUT Soil Moisture: Soil is the common component for most of the IOUT applications. Soil Moisture (SM) has been part of sensing in IOUT applications for crop production and agriculture. It is being used for measuring water content for decades. Earlier it was done manually by using hand-held devices, however, it has now been replaced by automated technologies due to difficulties of getting readings in remote fields.There has been much evolution in wireless data harvesting technologies for provision of real-time soil moisture data for decision making. It has helped a lot in improving water-management for many farm IOUTs [34]. Some of the major SM measurement methods are described below:

- Gravimetric Sampling is a method to measure the volumetric water content of the soil by using ration of dry and wet soil mass with pore spaces. The sampling is done manually and soil samples, taken from the field, are oven dried [11, 36].
- Resistive sensors [19] works on the electrical conductivity of water. It measures change in resistance due to water in soil. An accurate SM reading is highly dependent on calibration of sensors.
- Capacitive sensors measures works on change in capacitance due to water in soil. An accurate SM reading is highly dependent on calibration of sensors. These sensors are more accurate then resistive sensors, however, they are every expensive and are being used by commercial UTs.
- Ground Penetrating Radar (GPR) [49, 82], SalamChapter takes readings on the basis of absorption and reflection of electromagnetic (EM) waves. It uses

frequency sweep, impulse and frequency modulated technologies for SM sensing. GPRs are used to measure near surface (up to 10cm) SM readings.
- Neutron scattering probes [25, 65] and gauges measure estimating change in neutron flux density with respect to water in the soil. it uses radiation scattering techniques and are most accurate probes used for taking SM readings in the field. However, they require specific licenses to be used.
- Other famous SM measuring techniques are: Gamma ray attenuation [90], frequency-domain reflectometry (FDR) [160] and time-domain reflectometry (TDR) [109].

The burying depth of sensors ranges from 5 cm - 75 cm depending upon the root depth and type of the crop. It produces SM data which is used as input to create soil moisture maps for real-time decision making. the number of SM sensors deployed in the field are increasing at very fast rate. For example, Nebraska Agricultural Water Management Network [51, 68, 83] was initially built with only 20 grower in 2005. The number has increased to 1400 growers for adoption of SM sensors-based energy conservation and water management practices. Apart from in-situ sensing of soil moisture, other data sources for SM data are: NASA North American Land Data Assimilation System [38], NASA Soil Moisture Active Passive [18], US Climate Reference Network [48], TAMU North American Soil Moisture Database [47, 48], Soil Climate Analysis Network [45], and Soil Moisture and Ocean Salinity [44]. Web Soil Survey (WSS) [30] collects the US soil information and classifies them on the basis of region.

10.3.3 System Integration

IOUT generates glut of data from the field and it is not possible to locally process it because of limited processing power and energy resources. Therefore and the data data processing. The data can be store privately, publicly or can be shared among di erent users depending upon the user requirement [55, 186]. Many online applications and market places uses the big data sets to analyze region for better and maximized crop yield [185]. There are national databases for keeping the soil moisture data. In-situ SM sensors can be lined these databases to achieve accurate and detailed information on SM [3, 18, 33, 38, 47, 50]. Cloud services can be used to support real-time decision making and visualization. Therefore, cloud can be used as centralized data storage and processing system in IOUT. Integration of Cloud and IOUT adds scalability from field to big geographical area where unified network can be formed within various IOUT applications.

Moreover, after overcoming the storage and processing constraints, base stations can pull meteorological (from weather service) or soil data (from national service), combine this information with local UTs data for extended control on equipment. IOUT and Cloud integration opens new doors for more robust stakeholders in IOUT applications such as users, industry, trading companies. It would result in efficient and sustainable IOUT ecosystem. For example, in precision agriculture, in addition to integration of field data with di erent soil and weather databases, linking of UAVs and robotics can also be done in precision agriculture paradigm [35].

Weather the processing is being done locally or in the cloud, another challenge is to the integrating so many heterogeneous devices in a system. Reliable delivery of data from field to cloud and vice versa is an important functionality IOUT cloud architecture. This will not only provide a unified cloud connection of fields spread over vast geographical area but also enables to use data for assessment and improvement. There is also lack of standard interfaces which can provide seamless connectivity between various components of an IOUT system [24].

IOUT sense and communicate even the minor changes in the field including change in medium properties. IOUT applications generates big data and it is very important to correctly analyze this data to extract meaningful information and make real-time decisions to get better rate on investment. Therefore, developing a big data analytic is very important. For example, big data analytic in precision agriculture is: factors that may a ect crop yield, dividing the field into multiple zones based on particular applications such as nutrient, soil moisture, harvesting and productivity. It is important to analyze , e.g., water and energy consumption, and e ect on labor cost after adopting IOUT solution. Big data analytic are very important in showing the productivity and efficiency of the system. It attracts stakeholder and helps in widespread adoption of IOUT systems [31, 45].

10.4 IOUT Applications

10.4.1 Smart Lighting

One of the application area of IOUT is smart lighting [9, 8, 22]. In smart lighting, the cables are buried underground to provide intelligent lighting system. Fig. 10.4 shows the architecture of IOUT implementation in lighting.The IOUT-based smart lighting architecture consist of following basic components:

- Sensors - Attached to areas where lightning is required such as lamp posts, garage walls, and roadside poles etc.
- Above-ground (AG) Channel - Used for down-link communication from AG devices to buried UG devices.
- Underground (UG) Channel - Used for up-link communication from UG devices to AG devices.
- Lighting Infrastructure - IOUT lighting infrastructure includes: road lighting, airport runway lighting, household driveway, garage illumination, lamp posts and household driveway etc.

This architecture has many advantage over traditional over-the-air (OTA) lighting system. It eliminates wired networks completely. Moreover, installation of underground buried communication devices reduces the cabling complexity

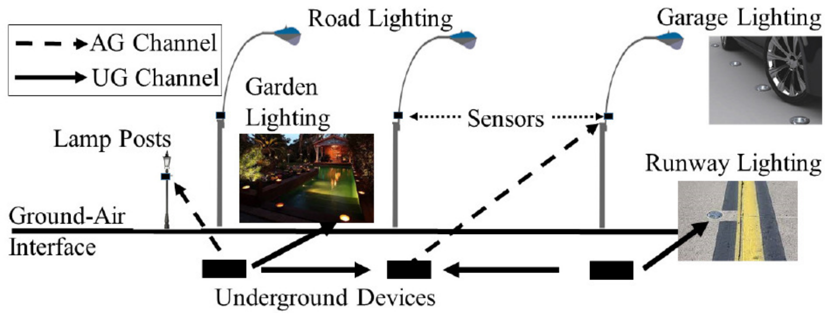


Fig. 10.4: IOUT-based smart lighting architecture [52]

significantly which, otherwise, is needed to power AG nodes. Finally, it also reduces the interference and spectral congestion. Communication in IOUT smart lightning is carried out by UG2AG communication channels.

One of the important task is in-depth analysis of UG channel while designing the smart lighting. A 2-wave model is presented in [70] which do not consider the lateral waves. [165] models the UG communication in tunnels and mines, however, it cannot be applied to smart lighting because of di erent propagation environment.

[49, 52] develops a statistical impulse response model for UG channel using the modeling approach presented in [78, 106, 152]. It modifies the model to suit the unique nature of underground channel. It assumes the correlation between the multi-path wave components to be negligible. Further more, it also assumes the phases at receiver side to be uniformly random and distributed over $[0, 2\pi)$.

It does so by performing extensive experiments on indoor (see Fig. 10.5 and field testbed to analyze the UG channel in smart lighting. The statistical model is developed by analyzing the power delay profile (PDP). It can generate wireless UG channel impulse response for di erent types of soil and soil moisture level, delay spread and coherence bandwidth statistics. The model gives the important feedback for designing the IOUT for smart lighting systems.

10.4.2 Urban UG Infrastructure

10.4.2.1 Overview

An important application for implementation of IOUT is urban underground infrastructure. Storm drains and sewers can overflow due to large amount of wastewater entering the pipes. In urban areas, city management collects millions of gallons of waster water and treat them in their waste facilities. This activity need to be monitored very carefully because extra waste water in the pipes can cause accumulation of water in pipes and ultimately leads to sewer overflows. Therefore, a smart monitoring of

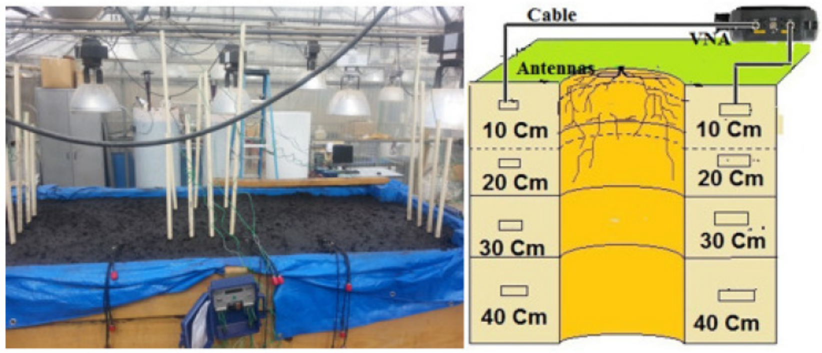


Fig. 10.5: Indoor testbed [52]

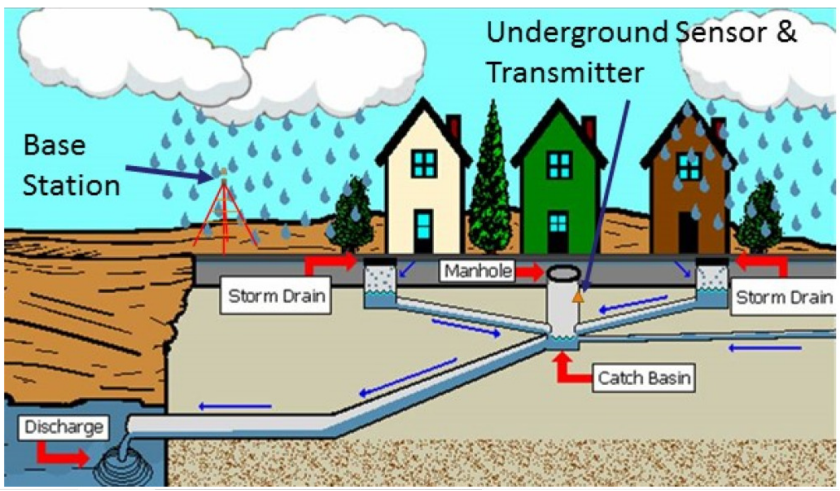


Fig. 10.6: IOUT-based Urband underground infrastructure: Smart wastewater system [44]

urban underground infrastructure is very important. IOUT can be used to develop smart applications for real-time monitoring of waste water or storm water over flow and timely warnings can be issued.

There are very limited solutions for this problem because of connectivity issues and extensive cabling requirement for implementation of such solutions. Fig. 10.6 shows the architecture of IOUT implementation in urban underground infrastructure. The IOUT-based urban underground architecture consist of following basic components:

- Sensors - Attached to underground pipes for sensing the incoming water and communicating the overflow, if happens.

Fig. 10.7: Layers of stratified underground medium [44]

- Wireless underground communication technology [62]- Communication infrastructure connects the sensors and base stations to communicate data to the control systems.
- Base Stations - Base stations collects data from the underground sensor nodes and sends it to the control center/cloud for decision making.
- Urban Infrastructure - Urban infrastructure includes roadside traffic poles which are used to implement above-ground communication technology with the underground sensors.

10.4.2.2 Path Loss Model for Urban UG Infrastructure

As discussed in previous section, underground sensors has to communicate with road-side pole for communicating the status of water in the pipes. The medium of communication in this case would be road. Road is a complex medium which is made up of multiple layers: asphalt, air and soil (see Fig. 10.7). Therefore, it is important to understand the e ect of each layer of the medium to achieve long range of communication. To that end, authors in [28, 44, 138], authors have done a path loss analysis for improving wireless UG communication in urban underground IOUT applications of waster water monitoring. The path loss has been empirically evaluated in di erent UG communication media and with thickness of layers in striated medium. They used Friis equation [74] to calculate the path loss in each layer. Th received signal power in a layered medium can be written as [44, 177]:

$$P_r = -L_m + G_r + P_t + G_t \ , \tag{10.1}$$

where L_m is the attenuation due to layered medium. L_m is calculated as:

$$L_m = L_{fs} + L_l, \tag{10.2}$$

where L_{fs} is over-the-air path loss and L_l extra attenuation due to EM wave propagation in the layered medium. It is given as:

$$L_{fs} = 33.2 + 20log(d) + 20log(f), \tag{10.3}$$

$$L_l = \sum_{n=0}^{N-1} L_n, \tag{10.4}$$

where L_n gives the attenuation in the *n-th* layer. L_n depends upon number of factors such as dielectric permittivity of the layer and the wavenumber of the medium. The wavenumber of the medium is given as $j\beta + \alpha = \gamma$ where

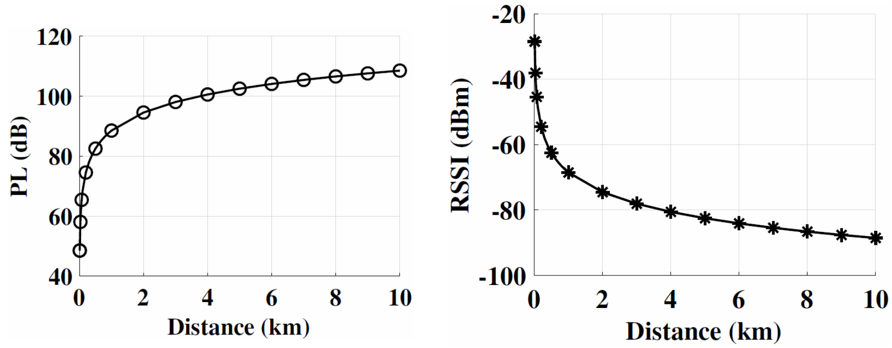
$$\alpha = \omega \sqrt{\frac{\mu\epsilon\prime}{2}\left[\sqrt{1 + (\frac{\epsilon\prime\prime}{\epsilon\prime})^2} - 1\right]}, \tag{10.5}$$

$$\beta = \omega \sqrt{\frac{\mu\epsilon\prime}{2}\left[\sqrt{1 + (\frac{\epsilon\prime\prime}{\epsilon\prime})^2} + 1\right]}, \tag{10.6}$$

where ω = $2\pi f$= angular frequency, μ is magnetic permeability, ϵ' is the real and ϵ'' is real and imaginary part of permittivity. Propagation loss, L_n for $n - th$ layer is given as:

$$L_n[dB] = 20.\gamma.d.\log 10(e) \tag{10.7}$$

where $e = 2.71828$, and d represents the thickness of the $n - th$ layer. [44] also determined the dispersion in the medium layers, i.e., soil, asphalt and base gravel aggravate layer. The experiments showed that, generally, path loss increased with the increase in the distance, however, it was less than 100 dB till 4km. Similarly, received signal strength decreased rapidly till 2 km, however, after 2 km, i.e., greater than 2km, the smooth decrease is observed. Both results are shown in Figs. 10.8Therefore, they concluded that upto 4km of communication range can be achieved, if propagation loss of a stratified medium is properly modeled.



(a) (b)

Fig. 10.8: (a) E ect of distance on path loss [44], (b) E ect of distance on RSS [44]

10.4.3 Oil & Gas Reservoirs

10.4.3.1 Overview

As per international energy agency (IEA), the energy demand of the world is going to increase significantly by 2030 [79]. The major portion of this increase originates from oil and gas industries, however, the challenging environment of Oil and Gas sector is failing to meet such a huge energy requirements. An important aspect of oil and gas industry reservoir is to obtain real-time information. IOUT is an enabling technology for optimized operation of oil and gas industry. These operations includes production, flow monitoring, and reservoir monitoring [87].

The challenging conditions of Oil and Gas sector has limited the application of traditional wireless networks. Therefore, magnetic induction (MI) based technology is being proposed as an enabling technology to develop a sensing system [2, 56, 161]. MI uses magnetic fields as major source of transferring communication. It's counterpart, EM waves, are highly e ected by the properties of underground environment and requires large antennas for the implementation [70]. On contrary, MI is not e ected by these properties. As large antennas are not feasible for IOUTs, MI uses tine coils as antennas, hence, are more practical choice for the implementation in IOUT.

10.4.3.2 MI-BASED IOUT SETUP

An MI-based IOUT network is shown in Fig. 10.9 which consists of randomly distributed *N* sensor nodes (underground things (UTs)) and *M* aboveground networking equipment (anchors). The UTs are injected to sub-surface area by hydraulic fracturing [76]. UTs are uniformly distributed with position represented as $S = s_{i}{}_{i=1}^{N}$ where $s_i = x_i, y_i, z_i$ are 3D position coordinates of *i*-th UT. Similarly, position of the *j*-th

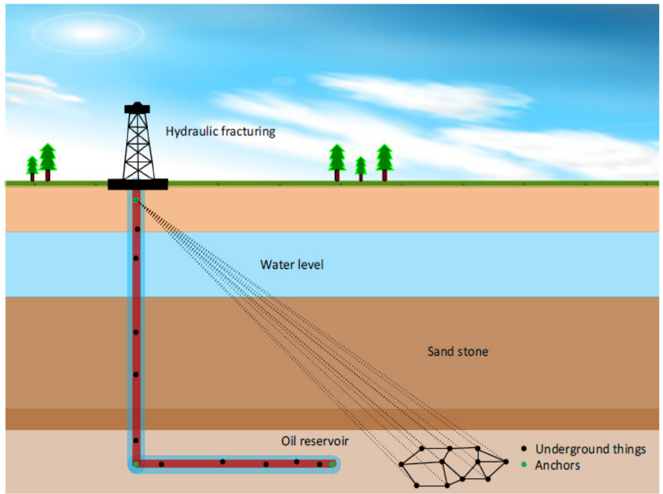


Fig. 10.9: Architecture of MI-based IOUT reservoirs [114]

anchor is given as $s_{j}{}_{j=1}^{M}$ where $s_j = x_j, y_j, z_j$. Moreover, position of the anchor is well known and are attached to the fracturing well.

Large dipole antennas are used by the anchors to communicate with UTs. Downlink channel (anchor → UT) is single hop because of extended transmission capabilities provided by the large dipole antenna. Downlink channel is represented by dotted black lines in Fig. 10.9. On contrary, uplink (UT → anchor) communication is multi-hop because of low power and transmission of UTs [167]. Uplink channel is represented by solid red lines in Fig. 10.9. High communication range for anchors is assumed because of the possibility of attaching them to external power sources. Waveguide structure of the coil is used to extend the communication range of MI coils [166].

UTs communicate with the other UTs and anchors using magnetic induction. A successful communication requires a proper coupling between the coils. Therefore, to receiver strong signal, a tri-directional coil receiver structure is proposed in [169]. the advantage of this coil structure is omni-directional coverage provided by it. From the perspective of magnetic induction, received and transmitted power are related as [110]:

$$P_{r_j} = \frac{\omega \mu P_{t_i} N_{r_j} N_{t_i} r_{t_i}^3 r_{r_j}^3 \sin^2 \alpha_{ij}}{16 R_0 d_{ij}^6}, \tag{10.8}$$

where P_{t_i} is transmitted power, ω and μ denotes the angular frequency and soil permeability. Diameter of receiver and sending coil is given by r_{r_i} and r_{t_i}, respectively. N_{r_j} denotes the total turns in receiver coil, α_{ij} denotes the angle between both transmitting and receiving coil, R_0 give $d_{ij} = \| \mathbf{s}_i - \mathbf{s}_j \|$ represents the distance between the sending and receiving destination coils. Equation 10.8 is also validated empirically in [169]. Equation 10.8 do not consider the skin depth e ect because of low frequencies, however, high frequencies are used for the soil, therefore, it is necessary to consider skin depth e ect for such cases. For skin depth e ect, distance between two UTs can be modified as:

$$\hat{d}_{ij} = f(P_{r_j}) = \arg\left\{d_{ij}|\Theta\right\} \tag{10.9}$$

where θ is given in [97] as:

$$\Theta = 10^{\frac{(P_{t_i} - P_{r_j})}{10}} - 1 = \frac{16 R_{0_t} R_{0_r} d_{ij}^3}{\omega^2 \mu^2 N_{t_i} N_{r_i} r_{t_i}^3 r_{r_j}^3 G^2(\sigma, \omega, d_{ij})}. \tag{10.10}$$

In equation 10.10, $G^2(\sigma, \omega, d_{ij})$ is the additional loss due to skin depth e ect and σ denotes the soil electrical conductivity.

10.4.3.3 IOUT application in Oil and Gas Reservoir

In [113], a MI-based localization technique for Oil and Gas reservoir is proposed and evaluated using Cramer Rao Lower Bound (CRLB). The distance between any two UTs *i* and *j* in MI-based IOUT is given by equation 10.9. As the transmission range of MI nodes is limited, so each node has to estimate only the distance between itself and nearby nodes. These distances are communicated to central control room, where missing distances are computed using matrix completion strategy as:

$$\rho_{ij} = \begin{cases} \hat{d}_{ij} & \text{if } d_{ij} \leq d_m, \\ \hat{d}_{ih(1)} + \sum_{k=1}^{L-1} \hat{d}_{h(k),h(k+1)} + \hat{d}_{h(L)j} & \text{otherwise,} \end{cases}$$

where d_m is maximum transmission distance, *L* is total hops between node *i* and *j*, and $h(1), \ldots, h(L)$. All ρ_{ij} values will result in diagonal squared geodesic distance matrix (SGDM) as given below:

$$\boldsymbol{\Psi} = \begin{bmatrix} 0 & \cdots & \rho^2_{i,(N+M)} \\ \vdots & \ddots & \vdots \\ \rho^2_{(N+M),1} & \cdots & 0 \end{bmatrix}. \tag{10.11}$$

where Ψ is square symmetric matrix where $\rho_{ij} = \rho_{ji}$ and $\rho_{ii} = 0$. After creating Ψ, the author employs dimensionality reduction technique to convert and visualize high dimensional distances into low-dimensional coordinates [112]. For this case three dimensional architecture, Isomap technique considered more suitable [172]. Isomap reduces the distances from high dimension to lower 3 dimensional coordinates. It does so by minimizing the following functions:

$$\Phi(\mathbf{S}) = \sum_{ij}(\rho_{ij}^2 - \parallel \mathbf{s}_i - \mathbf{s}_j \parallel^2), \tag{10.12}$$

where $\parallel \mathbf{s}_i - \mathbf{s}_j \parallel^2$ is the euclidean distance between nodes *i* and *j*. Another approach by Kruskal [90], applies a centering operator to SDGM, i.e., $(-\frac{1}{2} = \mathbf{G\Psi G}$, and gives a double centered matrix ($\mathbf{H} = -\mathbf{G\Psi G}^T/2$), where $\mathbf{H}$ is given as follow:

$$h_{ij} = -0.5\left(\rho_{ij}^2 - \frac{1}{T}\sum_{i=1}^{T}\rho_{ij}^2 - \frac{1}{T}\sum_{j=1}^{T}\rho_{ij}^2 - \frac{1}{T^2}\sum_{i=1}^{T}\sum_{j=1}^{T}\rho_{ij}^2\right),$$

In above equation $T = N + M$. Eigenvalue decomposition of $\mathbf{H}$ gives:

$$\widetilde{\mathbf{S}} = \mathbf{V}\sqrt{\mathbf{U}}, \tag{10.13}$$

$\mathbf{V}$ is the eigenvector of $\mathbf{H}$ and $\mathbf{U}$ is the eigenvalues of $\mathbf{H}$. The 3D coordinates are relative to each other not with respect to actual coordinate system. These local coordinates are converted to global geographical coordinates using Helmert transformation [184] or Procrustes analysis [43]. The location of the nodes are calculated as follow:

$$\hat{\mathbf{S}} = \varpi\varsigma(\widetilde{\mathbf{S}}) + \tau \tag{10.14}$$

where ϖ, ς, and τ are the di erent factors for rotation, scaling an translation, respectively. These factors are dependent upon the number fo anchors being used. The cost function of Procrustes analysis is givens as:

$$f(\boldsymbol{\varpi},\boldsymbol{\tau},\varsigma) = \sum_{i=1}^{M}(\widetilde{\mathbf{s}}_i - \varsigma\boldsymbol{\varpi}^T\mathbf{s}_i - \boldsymbol{\tau})^T \times (\widetilde{\mathbf{s}}_i - \varsigma\boldsymbol{\varpi}^T\mathbf{s}_i - \boldsymbol{\tau}) \tag{10.15}$$

The optimal values of ϖ, ς, and τ is calculated by minimizing equation 10.4.3.3. To that end, it is assumed that centroid of the real and estimated anchor location is $\mathbf{c}_a = \frac{1}{M}\sum_{i=1}^{M}\mathbf{s}_i$ and ,$\mathbf{c}_e = \frac{1}{M}\sum_{i=1}^{M}\hat{\mathbf{s}}_i$ respectively. Rewriting equation 10.4.3.3 by putting values of c_a and c_e as:

$$\begin{aligned} f(\boldsymbol{\varpi},\boldsymbol{\tau},\varsigma) = \sum_{i=1}^{M}\Bigg(& (\widetilde{\mathbf{s}}_i - \mathbf{c}_e) - \varsigma\boldsymbol{\varpi}^T(\mathbf{s}_i - \mathbf{c}_a) \\ & + \widetilde{\mathbf{s}}_i - \varsigma\boldsymbol{\varpi}^T\mathbf{s}_i - \boldsymbol{\tau}\Bigg)^T \\ & \times \Bigg((\widetilde{\mathbf{s}}_i - \mathbf{c}_e) - \varsigma\boldsymbol{\varpi}^T(\mathbf{s}_i - \mathbf{c}_a) \\ & + \widetilde{\mathbf{s}}_i - \varsigma\boldsymbol{\varpi}^T\mathbf{s}_i - \boldsymbol{\tau}\Bigg), \end{aligned} \tag{10.16}$$

The optimal values of τ is obtained by solving equation 10.16:

$$\boldsymbol{\tau} = \mathbf{c}_e - \varsigma \boldsymbol{\varpi}^T \mathbf{c}_a. \tag{10.17}$$

Furthermore, assuming that $\mathbf{c_e} = \mathbf{c_a} = 0$ and putting value of τ in equation 10.16 gives:

$$f(\boldsymbol{\varpi},\boldsymbol{\tau},\varsigma) = \sum_{i=1}^{M} (\mathbf{s}_i - \varsigma \boldsymbol{\varpi}^T \mathbf{s}_i)^T (\mathbf{s}_i - \varsigma \boldsymbol{\varpi}^T \mathbf{s}_i). \tag{13}$$

It is important to note that equation 10.4.3.3 is a convex function. Hence, this equation is di erentiated with respect to ς to obtain the optimal value of ς:

$$\varsigma = \frac{\mathrm{Tr}\left(\mathbf{S}_a \boldsymbol{\varpi} \widetilde{\mathbf{S}}_e^T\right)}{\mathrm{Tr}\left(\mathbf{S}_a \widetilde{\mathbf{S}}_e^T\right)} \tag{14}$$

where the function Tr($\cdot$) is the trace operator. Lastly, the eigenvalue decomposition of $\mathbf{S}_a \widetilde{\mathbf{S}}_e^T$ is done to obtain the optimal value of ϖ.

A proposed method is then analyzed by calculating CRLB as follow:

$$\mathrm{CRLB} = \mathbf{I}_{x,x}^{-1} + \mathbf{I}_{y,y}^{-1} + \mathbf{I}_{z,z}^{-1}. \tag{10.18}$$

The proposed technique is evaluated for e ect of coil size, number of coil turns, and transmit power on localization accuracy of the technique and shown that it surpasses the performance of other localization technique in both aspects.

10.5 IOUT Testbeds

Academic IOUT Testbed: IOUT can be used to estimate the water and fertilizer quantity to be applied using irrigation control system. A testbed in South Central Agricultural Lab (SCAL) in Clay Center, Nebraska [19, 33], covers an area of 41 acres with advanced center pivot irrigation system installed in it. The purpose of this testbed is to study long-term e ect of crop water and nutrient consumption, variable rate irrigation and fertigation, relation between the crop water stress and yield, development of crop production function, and other related topics under the settings of full and limited irrigation [19, 40, 45]. The testbed consist of a solar panel to provide sustainable energy, transmitting and receiving antennas, UTs with capabilities s of measuring temperature and soil moisture. It is a fully functional testbed and IOUT sensing nd communication can be investigated on it.

Another testbed developed for dynamically controlling soil moisture for IOUT wireless communications experiments inside greenhouse [39, 147]. It is enclosed in 100 in x 36 in x 48 wooden box. It has capacity of holding 90 cubic feet of packed soil

Table 10.1: Various IOUT systems developed by academic institutions [111]

Architecture	Sensors	Comm. Tech.	Node Density
Automated Irrigation System [77]	DS1822 (temperature) VH400 (soil moisture)	OTA, ZigBee (ISM)	One node per indoor bed
Soil Scout [104]	TMP122 (temperature) EC-5 (soil moisture)	UG, Custom (ISM)	Eleven scouts on field
Remote Sensing and Irrigation Sys. [86]	TMP107 (temperature) CS616 (soil moisture) CR10 data logger	OTA, Bluetooth (ISM)	Five field stations
Autonomous Precision Agriculture [9]	Watermark 200SS-15 (soil moisture) Data logger	UG, Custom (ISM)	Up to 20 nodes per field
SoilNet [58]	ECHO TE (soil moisture) EC20 TE (soil conductivity)	OTA, ZigBee (ISM)	150 nodes covering 27 ha
MOLES [170]	Magnetic Induction Communications	Magnetic Induction	Indoor Testbed
Irrigation Nodes in Vineyards [29]	Yield NDVI	VRI	140 irrigation nodes
Sensor Network for Irrigation Scheduling [16, 60]	Capacitance (soil moisture) Irromesh	OTA	6 nodes per acre
Cornell's Digital Agriculture [2]	E-Synch, Touch-sensitive soft robots Vineyard mapping technology, RTK	OTA	Field Dependant
Plant Water Status Network [107]	Crop water stress index (CWSI) Modified water stress index (MCWSI)	OTA	Two management zone
Real-Time Leaf Temperature Monitor System [39]	Leaf temperature Ambient temperature Relative humidity and Incident Solar radiation	OTA	Soil and plant monitors,
Thoreau [189]	Temperature, Soil moisture Electric conductivity and Water potential,	OTA	Based on Sigfox,
FarmBeats [175]	Temperature, Soil moisture Orthomosaic and pH,	OTA	Field size of 100 acres
Video-surveillance and Data-monitoring WUSN [72]	Agriculture data monitoring Motion detection, Camera sensor	OTA	In the order of several km
Purdue's Digital Agriculture Initiative [15]	Adaptive weather tower PhenoRover sensor vehicle	OTA	Field Dependant
Pervasive Wireless Sensor Network [183]	Soil Moisture, Camera	OTA	Field Dependant
Pilot Sensor Network [93]	Sensirion SHT75	OTA	100 nodes in a field
SoilBED [67]	Contamination detection	UG	Cross-Well Radar

and also have a drainage system. A controlled wireless communication experiments are carried out bu using antennas buried at di erent depths and distances.

Another MI-based testbed is developed in [168]. This testbed consist of coil buried in lab settings. It is used to study the e ect of MI wave guide e ect with di erent soil configurations SoilBED [29, 67] is used for the cross-well radar experiments. They are used for detection of contaminated materials in the soil and studying EM wave propagation. Thoreau [161] is another university level underground testbed which collects and curate the time related data on the cloud. It works on Sigfox design and operates in unlicensed band of 900 MHz. It measures soil moisture, water potential, temperature, and electrical conductivity with a very low data rate. There are many other IOUT testbed which are being used for the academic purpose. Table 10.1 provides a summary of all such test beds.

Commercial IOUT Solutions: Most of the commercial IOUT solutions uses OTA wireless communication and UTs with high-end sensors for measuring various properties of interest, hence, measurement is centralized. UTs can be connected to each other to form a mesh, however, mostly UTs deployed in the field connects with any base stations in the field.This base station have some sort of cellular or satellite communication capabilities. Fig. 10.10 shows the classification of various commercial IOUT systems. A highly desirable feature of IOUT system is modularity. Modularity allow for change and customization of application. Customized solutions

Table 10.2: Various commercially available IOUT systems developed by industry stakeholders [111]

Architecture	Sensors	Comm. Tech.	Node Density
IRROmesh [36]	200TS (temperature) Watermark 200SS-15 (soil moisture)	OTA, Custom (ISM) OTA, Cellular	Up to 20 nodes network mesh
Field Connect [11]	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 [4]	Plant water use Measure plant stress Soil moisture profile Weather and ET	OTA	25 SapIP nodes.
Automated Irrigation Advisor [24]	Tule Actual ET sensor	OTA	Field Dependant
Internet of Agriculture-BioSense [33]	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 Dependant
EZ-Farm [8]	Water Usage Big data, and Internet of Things Terrain, Soil, Weather Genetics Satellite info Sales	OTA	IBM Bluemix & IoT Foundation
Internet of Food and Farm (IoF2020) [35]	Soil moisture Soil temperature Electrical conductivity and Leaf wetness	OTA	Field Dependant
Cropx Soil Monitoring System [3]	Soil moisture Soil temperature and EC	OTA	Filed Dependant
Plug & Sense Smart Agriculture [13]	Temperature and humidity sensing, Rainfall, Wind speed and direction, Atmospheric pressure, Soil water content, and Leaf wetness	OTA	Field Dependant
Grain Monitor-TempuTech [21]	Grain temperature and Humidity	OTA	Multiple Depths in Grain Elevator
365FarmNet [26]	Mobile device visualization tool for IOUT data	OTA	Field Dependant
SeNet [42]	Sensing and control architecture	OTA	Field Dependant
PrecisionHawk [28]	Drones for sensing Field map generation	OTA	Field Dependant
HereLab [7]	Soil moisture, Drip line psi and rain	OTA	Field Dependant
IntelliFarms [34]	YieldFax Biological BinManager	OTA	Field Dependant
IoT Sensor Platform [10]	IoT/M2M sensors	OTA	Field Dependant
Symphony Link[20]	Long Range Communications	OTA	Field Dependant

can be made for some specific application which will work out-of-the-box. Table 10.1 provides the summary of IOUT commercial solutions. These commercial solutions can be classified into following major classes:

- *Agricultural solutions:* Field Connect, by John Deere, uses eight sensor probes to transmits data for measuring temperature, wind speed, wind direction Sm at di erent depth, and leaf wetness. These probes are located at 1 mile, and in case of satellite communication, it is located at three miles. Mi-mosaTEK gives services of irrigation and fertilization solutions from small to large scale

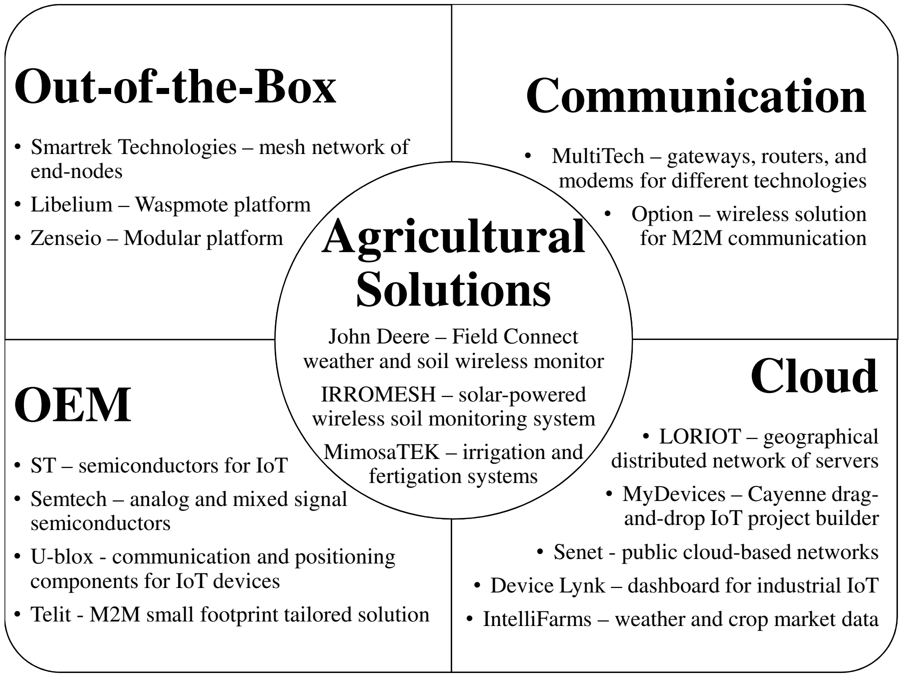


Fig. 10.10: Di erent types of commercially available IOUT systems [71]

.

farms [27, 41]. FarmBeats, developed by Microsoft, incorporates AI & IoT for agricultural solution.

- *Out-of-the-box packages:* Smartrek Technologies provide support for various sensors and gateways by developing weatherproof wireless nodes for outdoor settings and can easily be integrated into network mesh [26, 43]. Libelium provide solution, named as Plug & Sense Smart Agriculture solution [13], for sensing various farm parameters (SM, temperature etc.). It develops platforms and end-user devices with support for various communication standard such as LoRaWAN, Sigfox, ZigBee, WiFi, Bluetooth, RFID and LoRa etc. Their Waspmote platform has ability to attach 120 di erent sensors with connected sensor boards. Cropx's [3] IOUT comes with the hardware and software components for measuring soil properties (moisture, temperature, EC) for real-time decision making and irrigation. Precision Hawk's IOUT platform uses employs drones for sensing and generating field map using thermal, visual and multi spectral imaging.

- *OEM components:* OEM components are mainly used for manufacturing nodes at large scale, however, OEM devices are also required for prototyping and small scale production of specific UT. IoT internal components, e.g., accelerometers, MEMS microphones and gyroscope are developed by ST [46]. Various high-performance semiconductors and advance algorithms are supplied by Semtech [41].
- *Cloud-based services:* Cloud services can provide worldwide access to the information without having an technical knowledge of web programming. Stakeholders are not required to hire third party for configuring servers and make sense of collected data for decision making. LORIoT is one such cloud service which connect multiple distributed low latency networks through LoRa gateway. Some web service includes device management, cloud data storage, safe keeping of keys used for the encryption and translation of LoRaWAN to IP/IPv6 [40]. MyDevices helps IoT developer by providing their drag-and-drop IoT project builder called Cayenne. User can create accounts and use Cayenne (both web and mobile) for their IT devices registration and visualize the sensed data in customized dashboard.

10.5.1 Challenges

The combination of soil and communication components for wireless UG communications is very unique. This combination requires us to study the fundamental concept of communications from a completely di erent perspective. The factors which directly a ect the soil may also influence the performance of UG communications. The network topology should be robust enough to support and cope with the rapidly changing channel conditions. One of the most important soil properties to consider while designing IOUT is Volumetric Water Content (VWC). Therefore, it is very important to study the spatial and temporal variation of VWC in the region of IOUT deployment. Soil composition of a field location plays an important role in tailoring the topology design to meet the criteria of underground channel of that location, hence, it should be thoroughly investigated. For example, if the IOUT is being deployed in a region where soil composition has significant spatial heterogeneity, it will be beneficial to study the di erent node densities and inter-node distances. In addition to the soil type, VWC variations due to seasonal changes also significantly a ect the communication performance [49]. Some of the environmental parameters were studied by performing experiments. These experiments show that VWC has an adverse e ect on the UG communications. Therefore, while designing protocol for IOUT, these environment parameters must be considered. IOUT protocols must allow the dynamic adjustment of operational parameters to adapt to changes in surroundings. Lastly, IOUT feasibility is dependent on the investigation of multiple other factors that were not considered for traditional WSNs, e.g., soil composition and VWC. To this end, detailed channel characterization of wireless UG communication is required. There is some positive aspect of UG environment as well, e.g., its temporal stability.

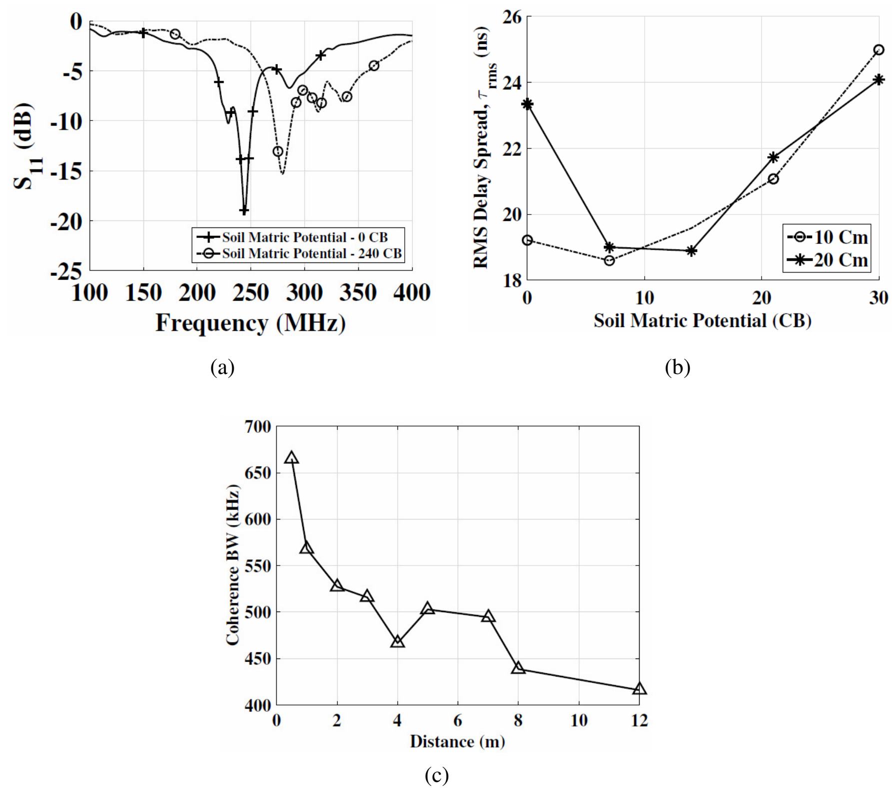


Fig. 10.11: (a) E ect of soil moisture on antenna return loss at varying frequencies and fixed depth of 40cm in sandy soil [139], (b) E ect of soil moisture on RMS delay spread at T-R separation distance of 50cm and two depths of 10cm and 20cm [139], (c) E ect of T-R separation (distance) on coherence bandwidth at fixed depth of 20cm in silty clay loam soil [139]

These positive aspects need to be exploited and studied further to achieve reliable and energy-efficient communication [50].

Characteristics of UG wireless channel is the key factor which determines the data rate of communication in IOUT. If it is not well modelled, communication performance of IOUT su ers. Therefore, experimentation is needed for its characterization. Moreover, soil with communication components (antenna and wireless UG channel) gives unique IOUT performance characteristics. Fig. 1.3 shows the empirical measurements [139], [145] for the soil e ect on coherence bandwidth of UG channel and antenna bandwidth.

Soil characteristics such as soil type, soil moisture, soil depth and burial distance have an e ect on communication performance [177]. It can cause dynamic changes in root mean square (RMS) delay spread, antenna return loss, and impulse response of the channel. Fig. 10.11(a) shows the empirical values for antenna return loss (at depth of 40cm in sandy soil) in response to change in soil moisture. Soil moisture is represented by soil matric potential (CB) and both have an inverse relation, i.e., large values of matric potential indicate low soil moisture. Similarly, zero matric potential represents a near situation condition. It can be seen that resonant antenna frequency jumps from 244 MHz to 289 MHz when matric potential value increases from 0 CB to 240 CB. This significant increase requires a dynamic change in operational frequency to achieve maximum bandwidth otherwise operation frequency will exceed the range of resonant frequency and antenna bandwidth causing the degradation in performance [62, 72]. Similarly, decreasing the soil moisture causes the antenna bandwidth to increase from 14 MHz to 20 MHz. Accordingly, the soil moisture will also have a significant impact on system bandwidth [20, 25].

Soil texture is the measurement of percentage of sand, clay and silt in the soil. Table 1.3 lists the classification of soil on the basis of texture and corresponding particle size distribution. Fig. 10.11(b) plots change in RMS delay spread with soil moisture at a distance of 50cm and depths of 10cm and 20cm in silt loam. It can be seen that RMS delay spread, initially, decreases when soil moisture is decreased (0 CB to 8 CB). Afterwards, RMS delay spread in increased consistently. The occurrence of these variations with short period of time due to external impact, e.g., rain, may cause wireless UG channel to be frequency-selective.

Fig. 10.11(c) shows the statistics of coherence bandwidth as a function of distance. For distances up to 12m, coherence bandwidth lies in the range of 411 kHz and 678 kHz. Use of traditional communication techniques with this small coherence bandwidth may limit the achievable data rate in IOUT communications.

These sources provide extensive data on soil moisture and temperature for vast geographical areas and extend the Web Soil Survey (WSS) [30, 43].

IOUT Other Soil Medium Properties: Soil properties, other than the soil moisture, which can be measured using sensing technologies are: acidity (pH) [65, 154], organic matter in the soil, sand percentage, nutrients such as P, Mg, Ca, OM, base saturation K, base saturation Mg, base saturation Ca, K/Mg, Ca/Mg ratios, and CEC [85, 94, 95], and clay and silt particles [46, 156]. These properties can be used to develop soil map. However, due to cost, size and technology limitations, real-time and in-situ measurement of these properties is still a challenge.

IOUT Yield Monitoring: Yield monitoring is the application of IOUT in agriculture. It is used to give spatial distribution of crop yield when the growing season is ending. It is used to make long-term decision in IOUT agriculture [32, 54, 91, 99]. The yield data is collected automatically by deploying yield monitors on the IOUT farm moving equipment. These equipment collect data during the harvesting season. Grain containers are equipped with mass flow sensors (e.g., Force Sensor by Ag Leader) which records grain inflow with location. Di erent geographic information systems (GIS), e.g., Mapinfo, ArchInfo, and Environment System Research International tools can be used to analyze the data.

IOUT Electrical conductivity and topography surveys: Electrical conductivity (EC) of the soil can be defined as the soil ability to conduct electricity [98]. EC data, combined with the field topography (slope and elevation), can be used to get insights on crop yield. EC measures the nitorgen usage, drainage, water holding and cation-exchange capacity, and rooting depth. EC classifies whole field into multiple zones then various precision agriculture technologies (e.g., VRT) are applied based on zoning. There are various methods to perform EC mapping such as visible-near infrared reflectance spectroscopy (VNIR) [55, 57], apparent electrical conductivity (ECa) [66], and electromagnetic Induction (EMI) [45, 162]. Commercial tools for EC mappings includes: EC400 sensors combined with GPS systems [27, 89] and Veris 3100 [25, 29].

IOUT Weather and environmental sensing: The performance of IOUT systems is highly dependent upon weather and environmental conditions such as wind speed, wind direction, temperature of soil and air, humidity, rainfall, and solar emissions. Weather and environmental sensors are used to measure all the mentioned e ects. Such information is very useful in realization of real-time, informed and timely decisions in IOUT systems. Some of the examples of these sensors are: Field Connect solution [37] and Mesoscale Network (MesoNet) [12]. MesoNet is a large-scale network of weather and environment sensing nodes covering large geographical areas. It detects major weather patterns and can be used to provide real-time information when combined with IOUT systems

IOUT Macro-nutrients sensing: Underground environment provides various important natural resources also including macro-nutrients. Macro-Nutrients (e.g., potassium, phosphorous and nitrogen) are very important for some IOUT applications. In agricultural IOUT, for example, calculating and assessing these nutrients helps in determining the fertilizer application and impact in the future. In [30, 102], a sensing method is presented for detection of sulfate and nitrate concentration in natural water resources. This method uses planar electromagnetic sensors and senses nitrate and sulfate levels using correlation of the their concentration and sensor array impedance. the study concludes sensor impedance is inversely proportional to the concentration of the chemicals. Other macro-nutrient sensing approaches that can be used in IOUT system includes: ATR spectroscopy, VIS-NIRS spectroscopy, and Electrochemical approach. However, these approaches only sense on desired ion because their membrane respond to only one ion [30, 95]. Major challenge would be to develop a detector array of macro-nutrients sensing for accomplishing multi-ion sensing [26, 85].

IOUT Precision Agriculture technologies: As discussed earlier, precision agriculture is one of the major area and precision agriculture is major application of IOUT system. There are tons of technologies playing a very important role in adoption of precision agriculture practices which will be presented here as useful IOUT tools. These technologies include: auto-steering and VRT, precision planting, GIS systems, geolocation, soil sampling, field analysis map generation and drones. Precision planting [14] involves seeding based on fine predetermined inter-plant distance and laser robot with an ability of automated weed zapping. Farm devices are aligned using robovator technology. Multiple zones can be created on the basis fo field conditions using GPS [35, 44, 188]. For the improvement of crop yield, Variable rate fertilizer application [32, 53] is also very important. Another major component of IOUT system is the drone with wireless communication capabilities. Deere &

Co. has developed a GreenStar Lightbar [6] to measure width and location in the row crops. Another device, TK-GPS [23], is capable of performing real-time soil mapping.

These sensing technologies can become the stepping stone for development of IOUT systems. Inexpensive sensors and wireless communication make their integration with IOUT control system possible. One of the major component, for realization of real-time decision making in IOUT systems, is the wireless communication between the heterogeneous sensor equipment. Furthermore, adoption rate of sensor technologies can be increased by a connected, secured and reliable IOUT systems which in-turn will be very helpful in development of improved sensing technologies in IOUT [24].

Some of the challenges in design and implementation of IOUT systems are given below:

1. When being deployed in large areas, cost-efficient and simple IOUT devices are desired which can sustain all harsh environmental e ects.
2. Improving UTs will consequently increase the energy demand leading to less battery life. Therefore, energy harvesting, sustainable energy resources and energy efficient operations are the major challenges in IOUT systems [53].
3. Due to heterogeneity in UTs, seamless integration of UTs with communication systems is required.
4. For farm IOUT, multi-modal and inexpensive sensors are required which can sense physical parameters of soil in addition to moisture. Although, SM provides important information for irrigation system, however, in-situ sensing of soil chemicals is required for variable rate fertigation.
5. Secure mechanisms are required to store and transfer information from the fields. Moreover, solutions are required to merge data from all the fields for improved decision making in private and secure manner.
6. Seasonal changes can alter the working of IOUT equipment, e.g., freezing temperature can increase power consumption. Equipment can be set to sleep mode when monitoring is not needed [31].
7. UTs must be able to dynamically change their operational parameters such as frequency, modulation schemes and error encoding schemes to adapt to changes in communication medium.
8. Impact of medium properties, e.g., soil in agriculture, must be modeled. A detailed analysis fo these properties can support in building scalabale and reliable IOUT architecture.
9. There is a dire need for specialized link and network layer protocols for UG communications which can lead to robust data transfer in IOUT.

References

[1] (2020) Bluetooth. `https://www.bluetooth.com/bluetooth-technology`

[2] (2020) Cornell Digital Agriculture. https://cuaes.cals.cornell.edu/digital-agriculture
[3] (2020) Cropx soil monitoring system. https://www.cropx.com/
[4] (2020) Dynamax SapIP Wireless Mesh Network. http://dynamax.com/products/data-loggers/sapip-wireless-mesh-network
[5] (2020) Extended Coverage - GSM – Internet of Things (EC-GSM-IoT). URL https://www.gsma.com/iot/extended-coverage-gsm-internet-of-things-ec-gsm-iot/
[6] (2020) Greenstar lightbar. https://www.deere.com/en_INT/products/equipment/agricultural_management_solutions/guidance_and_machine_control/greenstar_lightbar/greenstar_lightbar.page
[7] (2020) Herelab. www.Herelab.io
[8] (2020) IBM EZ-Farm. https://www.ibm.com/developerworks/community/blogs/dfa2dc54-5a14-4cf8-91e0-978bfd59d0d4/entry/IBM_Research_Africa_Enhancing_the_way_we_farm?lang=en
[9] (2020) IEEE 802.11, The Working Group Setting the Standards for Wireless LANs. URL http://www.ieee802.org/11/
[10] (2020) Iot sensor platform. http://zenseio.com/zenseio-platform
[11] (2020) John deere field connect. https://www.deere.com/
[12] (2020) The Oklahoma Mesonet. http://www.mesonet.org/
[13] (2020) Plug and sense smart agriculture. http://www.libelium.com/products/plug-sense/models/#smart-agriculture
[14] (2020) Precision planting. http://www.precisionplanting.com
[15] (2020) Purdue's Digital Agriculture Initiative. http://mailimages.purdue.edu/vo/?FileID=ac13556e-8057-487f-a01b-6914f848cc4c
[16] (2020) Sensor network for irrigation scheduling. http://soilphysics.okstate.edu/research/moisst/2017-moisst-workshop/Taghvaeian%20MOISST%202017.pdf/at_download/file
[17] (2020) Sigfox. https://www.sigfox.com/en
[18] (2020) SMAP. URL https://smap.jpl.nasa.gov/
[19] (2020) Soil mositure sesnor. http://www.irrometer.com/sensors.html
[20] (2020) Symphony link. https://www.link-labs.com/symphony
[21] (2020) Temputech wireless sensor monitoring. http://www.temputech.com/
[22] (2020) Thread. https://www.threadgroup.org/technology/ourtechnology
[23] (2020) Tk-gps. http://www.tk-star.com/
[24] (2020) Tule. https://www.tuletechnologies.com/
[25] (2020) Veris technology. https://www.veristech.com/the-sensors/v3100
[26] (2017) 365 FarmNet. https://www.365farmnet.com/en/
[27] (2017) Mimosatek. www.mimosatek.com, [Accessed: 2017-09-30]
[28] (2017) PrecisionHawk Drone Data Platform. http://www.precisionhawk.com/agriculture

[29] (2017) Vri study. http://proceedings.esri.com/library/userconf/proc15/papers/185_435.pdf
[30] (2017) Web soil survey home. https://websoilsurvey.sc.egov.usda.gov/
[31] (2017) Zigbee alliance. www.zigbee.org
[32] (2020) Adapt-N. http://www.adapt-n.com/
[33] (2020) Biosense. www.biosens.rs
[34] (2020) Intellifarms. www.intellifarms.com
[35] (2020) IoF2020. https://www.iof2020.eu/
[36] (2020) Irromesh wireless mesh system. http://www.irrometer.com/loggers.html#975
[37] (2020) John deere field connect. https://www.deere.com/en/technology-products/precision-ag-technology/field-and-water-management/field-connect/
[38] (2020) Ldas land data assimilation systems. https://ldas.gsfc.nasa.gov/nldas/
[39] (2020) Leaf monitor system. http://www.westernfarmpress.com/tree-nuts/uc-research-explores-continuous-leaf-monitor-system-maximize-irrigation-almonds
[40] (2020) Loriot | lorawan services and software. www.loriot.io
[41] (2020) Semtech. www.semtech.com
[42] (2020) Senet. www.senetco.com
[43] (2020) Smartrek technologies. www.smartrektechnologies.ca
[44] (2020) Smos. www.esa.int/Our_Activities/Observing_the_Earth/SMOS
[45] (2020) Soil climate analysis network (scan) data & products. www.wcc.nrcs.usda.gov/scan/
[46] (2020) St. www.st.com
[47] (2020) Tamu north american soil moisture database. soilmoisture.tamu.edu
[48] (2020) U.s. climate reference network. www.ncdc.noaa.gov/crn/
[49] Adamchuk V, Hummel J, Morgan M, Upadhyaya S (2004) On-the-go soil sensors for precision agriculture. Computers and Electronics in Agriculture 44(1):71 – 91
[50] of Agriculture UD (2014) Census of Agriculture. URL http://www.agcensus.usda.gov/
[51] Akkaş MA, Sokullu R, Balcı A (2015) Wireless sensor networks in oil pipeline systems using electromagnetic waves. In: 2015 9th International Conference on Electrical and Electronics Engineering (ELECO), IEEE, pp 143–147
[52] Akyildiz IF, Stuntebeck EP (2006) Wireless underground sensor networks: Research challenges. Ad Hoc Networks Journal
[2] Akyildiz IF, Stuntebeck EP (2006) Wireless underground sensor networks: Research challenges. Ad Hoc Networks 4(6):669–686

[54] Akyildiz IF, Sun Z, Vuran MC (2009) Signal propagation techniques for wireless underground communication networks. Physical Communication Journal (Elsevier) 2(3):167–183
[55] Algeroy J, Lovell J, Tirado G, Meyyappan R, Brown G, Greenaway R, Carney M, Meyer JH, Davies JE, Pinzon ID (2010) Permanent monitoring: taking it to the reservoir. Oilfield Review 22(1):34–41
[56] Bansal R (2004) Near-field magnetic communication. IEEE Antennas and Propagation Magazine 46(2):114–115
[57] Bilgili AV, van Es H, Akbas F, Durak A, Hively W (2010) Visible-near infrared reflectance spectroscopy for assessment of soil properties in a semi-arid area of turkey. Journal of Arid Environments 74(2):229 – 238, DOI https://doi.org/10.1016/j.jaridenv.2009.08.011, URL `http://www.sciencedirect.com/science/article/pii/S0140196309002559`
[58] Bogena HR, Herbst M, Huisman JA, Rosenbaum U, Weuthen A, Vereecken H (2010) Potential of wireless sensor networks for measuring soil water content variability. Vadose Zone Journal
[59] de Carvalho Silva J, Rodrigues JJ, Alberti AM, Solic P, Aquino AL (2017) Lorawan—a low power wan protocol for internet of things: A review and opportunities. In: Computer and Energy Science (SpliTech), 2017 2nd International Multidisciplinary Conference on, IEEE, pp 1–6
[60] DeJonge KC, Taghvaeian S, Trout TJ, Comas LH (2015) Comparison of canopy temperature-based water stress indices for maize. Agricultural Water Management 156:51 – 62, DOI https://doi.org/10.1016/j.agwat.2015.03.023, URL `http://www.sciencedirect.com/science/article/pii/S0378377415001067`
[61] Dong X, Vuran MC (2011) A channel model for wireless underground sensor networks using lateral waves. In: Proc. of IEEE Globecom '11, Houston, TX
[62] Dong X, Vuran MC (2013) Impacts of soil moisture on cognitive radio underground networks. In: Proc. IEEE BlackSeaCom, Georgia
[9] Dong X, Vuran MC, Irmak S (2012) Autonomous precision agricultrue through integration of wireless underground sensor networks with center pivot irrigation systems. Ad Hoc Networks (Elsevier)
[19] Dong X, Vuran MC, Irmak S (2013) Autonomous precision agriculture through integration of wireless underground sensor networks with center pivot irrigation systems. Ad Hoc Networks 11(7):1975–1987
[65] Evett S, Steiner J (1995) Precision of neutron scattering and capacitance type soil water content gauges from field calibration. Soil Science Society of America Journal 59(4):961–968
[66] Farahani HJ, Khosla R, Buchleiter G (2020) Field ec mapping: a new tool to make better decisions. Crop series Soil; no 0568
[67] Farid A, Alshawabkeh A, Rappaport C (2006) Validation and calibration of a laboratory experimental setup for cross-well radar in sand. American Society for Testing and Materials (ASTM) Geotechnical Testing Journal 29(2)
[68] Ferguson H, Gardner W (1962) Water content measurement in soil columns by gamma ray absorption. Soil Science Society of America Journal 26(1):11–14

[11] Foth HD (1978) Fundamentals of soil science. Soil Science 125(4):272
[70] Franconi NG, Bunger AP, Sejdić E, Mickle MH (2014) Wireless communication in oil and gas wells. Energy Technology 2(12):996–1005
[25] Franz TE, Wahbi A, Vreugdenhil M, Weltin G, Heng L, Oismueller M, Strauss P, Dercon G, Desilets D (2016) Using cosmic-ray neutron probes to monitor landscape scale soil water content in mixed land use agricultural systems. Applied and Environmental Soil Science 2016
[72] Garcia-Sanchez AJ, Garcia-Sanchez F, Garcia-Haro J (2011) Wireless sensor network deployment for integrating video-surveillance and data-monitoring in precision agriculture over distributed crops. Computers and Electronics in Agriculture 75(2):288–303
[73] Gardner WR, Hyden RE, Linyaev EJ, Gao L, Robbins C, Moore J, et al. (2006) Acoustic telemetry delivers more real-time downhole data in underbalanced drilling operations. In: IADC/SPE Drilling Conference, Society of Petroleum Engineers
[74] Goldsmith A (2005) Wireless Communications. Cambridge University Press, New York, NY, USA
[75] Guo H, Sun Z (2014) Channel and energy modeling for self-contained wireless sensor networks in oil reservoirs. IEEE Trans Wireless Communications 13(4):2258–2269, DOI 10.1109/TWC.2013.031314.130835
[76] Guo H, Sun Z (2014) Channel and energy modeling for self-contained wireless sensor networks in oil reservoirs. IEEE Transactions on Wireless Communications 13(4):2258–2269
[77] Gutiarrez J, Villa-Medina JF, Nieto-Garibay A, Porta-Gandara MA (2014) Automated irrigation system using a wireless sensor network and gprs module. IEEE Transactions on Instrumentation and Measurement 63(1):166–176, DOI 10.1109/TIM.2013.2276487
[78] Hashemi H (1993) Impulse response modeling of indoor radio propagation channels. IEEE journal on selected areas in communications 11(7):967–978
[79] Helsinki F (2013) Dynamic communications for oil and gas
[80] Hernandez M, MacNeill DW, Reeves M, Kirkwood AD, Ruszka JP, Zaeper R, Lemke SR, et al. (2008) High-speed wired drillstring telemetry network delivers increased safety, efficiency, reliability, and productivity to the drilling industry. In: SPE Indian Oil and Gas Technical Conference and Exhibition, Society of Petroleum Engineers
[81] Hopkins J (2016) USDA ERS - ARMS farm financial and crop production practices: Tailored reports: Crop production practicesl. ersusdagov, Available: http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/tailored-reports-crop-pro
[82] Huisman J, Hubbard S, Redman J, Annan A (2003) Measuring soil water content with ground penetrating radar. Vadose zone journal 2(4):476–491
[83] Irmak S (2010) Nebraska water and energy flux measurement, modeling, and research network (NEBFLUX). Trans ASABE 53(4):1097–1115
[84] Karli R, Bouchalkha A, Alhammadi K (2017) Investigation of electromagnetic (em) wave attenuation in oil pipeline. In: 2017 International Conference on

Electrical and Computing Technologies and Applications (ICECTA), IEEE, pp 1–4
[85] Kim HJ, Sudduth KA, Hummel JW (2009) Soil macronutrient sensing for precision agriculture. Journal of Environmental Monitoring 11(10):1810–1824
[86] Kim Y, Evans RG, Iversen WM (2008) Remote sensing and control of an irrigation system using a distributed wireless sensor network. IEEE Transactions on Instrumentation and Measurement 57(7):1379–1387, DOI 10.1109/TIM.2008.917198
[87] Kissele S, Akyildiz IF, Gerstacker WH (2018) Survey on advances in magnetic induction-based wireless underground sensor networks. IEEE Internet of Things Journal 5(6):4843–4856
[20] Konda A, Rau A, Stoller MA, Taylor JM, Salam A, Pribil GA, Argyropoulos C, Morin SA (2018) Soft microreactors for the deposition of conductive metallic traces on planar, embossed, and curved surfaces. Advanced Functional Materials 28(40):1803020, DOI 10.1002/adfm.201803020
[89] Krishna K (2016) Push Button Agriculture: Robotics, Drones, Satellite-Guided Soil and Crop Management. Apple Academic Press, URL `https://books.google.com/books?id=NlmzDAAAQBAJ`
[90] Kruskal JB (1964) Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. Psychometrika 29(1):1–27
[91] Kukal MS, Irmak S (2017) Spatial and temporal changes in maize and soybean grain yield, precipitation use efficiency, and crop water productivity in the us great plains. Transactions of the ASABE 60(4):1189–1208
[92] Kulkarni A, Kumar V, Dhok SB (2018) Enabling technologies for range enhancement of mi based wireless non-conventional media communication. In: 2018 9th International Conference on Computing, Communication and Networking Technologies (ICCCNT), IEEE, pp 1–7
[93] Langendoen K, Baggio A, Visser O (2006) Murphy loves potatoes: Experiences from a pilot sensor network deployment in precision agriculture. In: Parallel and Distributed Processing Symposium, 2006. IPDPS 2006. 20th International, IEEE, pp 8–pp
[94] Laskar S, Mukherjee S (2016) Optical sensing methods for assessment of soil macronutrients and other properties for application in precision agriculture: a review. ADBU Journal of Engineering Technology 4
[95] Lin J, Wang M, Zhang M, Zhang Y, Chen L (2007) Electrochemical sensors for soil nutrient detection: Opportunity and challenge. In: International Conference on Computer and Computing Technologies in Agriculture, Springer, pp 1349–1353
[96] Lin SC, Akyildiz IF, Wang P, Sun Z (2014) Optimal energy-throughput efficiency for magneto-inductive underground sensor networks. In: 2014 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom), IEEE, pp 22–27
[97] Lin SC, Alshehri AA, Wang P, Akyildiz IF (2017) Magnetic induction-based localization in randomly deployed wireless underground sensor networks. IEEE Internet of Things Journal 4(5):1454–1465

[98] Lund E, Christy C, Drummond P (1999) Practical applications of soil electrical conductivity mapping. Precision agriculture 99:771–779

[99] Magri A, Van Es HM, Glos MA, Cox WJ (2005) Soil test, aerial image and yield data as inputs for site-specific fertility and hybrid management under maize. Precision Agriculture 6(1):87–110

[100] Markham A, Trigoni N (2012) Magneto-inductive networked rescue system (miners): Taking sensor networks underground. In: Proceedings of the 11th ICPS, ACM, IPSN '12, pp 317–328, DOI 10.1145/2185677.2185746

[101] Mwachaka SM, Wu A, Fu Q (2019) A review of mud pulse telemetry signal impairments modeling and suppression methods. Journal of Petroleum Exploration and Production Technology 9(1):779–792

[102] Nor ASM, Faramarzi M, Yunus MAM, Ibrahim S (2015) Nitrate and sulfate estimations in water sources using a planar electromagnetic sensor array and artificial neural network method. IEEE Sensors Journal 15(1):497–504, DOI 10.1109/JSEN.2014.2347996

[103] Oelze ML, O'Brien WD, Darmody RG (2002) Measurement of attenuation and speed of sound in soils. Soil Science Society of America Journal 66(3):788–796

[104] Pathak V, Kumar V, Barik RK (2018) Magnetic induction communication based transceiver coil and waveguide structure modeling for non-conventional wsns. In: 2018 9th International Conference on Computing, Communication and Networking Technologies (ICCCNT), IEEE, pp 1–7

[105] Petäjäjärvi J, Mikhaylov K, Hämäläinen M, Iinatti J (2016) Evaluation of lora lpwan technology for remote health and wellbeing monitoring. In: Medical Information and Communication Technology (ISMICT), 2016 10th International Symposium on, IEEE, pp 1–5

[106] Rappaport TS, Seidel SY, Takamizawa K (1991) Statistical channel impulse response models for factory and open plan building radio communicate system design. IEEE Transactions on Communications 39(5):794–807

[107] Rojo F, Kizer E, Upadhyaya S, Ozmen S, Ko-Madden C, Zhang Q (2016) A leaf monitoring system for continuous measurement of plant water status to assist in precision irrigation in grape and almond crops. IFAC-PapersOnLine 49(16):209 – 215, DOI https://doi.org/10.1016/j.ifacol.2016.10.039, URL `http://www.sciencedirect.com/science/article/pii/S2405896316316020`, 5th IFAC Conference on Sensing, Control and Automation Technologies for Agriculture AGRICONTROL 2016

[108] Rossel RAV, Bouma J (2016) Soil sensing: A new paradigm for agriculture. Agricultural Systems 148:71–74

[109] Roth K, Schulin R, Flühler H, Attinger W (1990) Calibration of time domain reflectometry for water content meaurement using a composite dielectric approach. Water Resources Research 26(10):2267–2273

[110] Saeed N, Nam H (2016) Cluster based multidimensional scaling for irregular cognitive radio networks localization. IEEE Transactions on Signal Processing 64(10):2649–2659

[111] Saeed N, Celik A, Alouini MS, Al-Na ouri TY (2018) Performance analysis of connectivity and localization in multi-hop underwater optical wireless sensor networks. IEEE Transactions on Mobile Computing 18(11):2604–2615

[112] Saeed N, Nam H, Haq MIU, Muhammad Saqib DB (2018) A survey on multidimensional scaling. ACM Computing Surveys (CSUR) 51(3):1–25

[113] Saeed N, Alouini M, Al-Na ouri TY (2019) 3d localization for internet of underground things in oil and gas reservoirs. IEEE Access 7:121769–121780, DOI 10.1109/ACCESS.2019.2937915

[114] Saeed N, Alouini MS, Al-Na ouri TY (2019) Toward the internet of underground things: A systematic survey. IEEE Communications Surveys & Tutorials 21(4):3443–3466

[24] Salam A (2018) Pulses in the sand: Long range and high data rate communication techniques for next generation wireless underground networks. ETD collection for University of Nebraska - Lincoln (AAI10826112), URL `http://digitalcommons.unl.edu/dissertations/AAI10826112`

[25] Salam A (2019) A comparison of path loss variations in soil using planar and dipole antennas. In: 2019 IEEE International Symposium on Antennas and Propagation, IEEE

[26] Salam A (2019) Design of subsurface phased array antennas for digital agriculture applications. In: Proc. 2019 IEEE International Symposium on Phased Array Systems and Technology (IEEE Array 2019), Waltham, MA, USA

[27] Salam A (2019) A path loss model for through the soil wireless communications in digital agriculture. In: 2019 IEEE International Symposium on Antennas and Propagation, IEEE, pp 1–2

[28] Salam A (2019) Sensor-free underground soil sensing. In: ASA, CSSA and SSSA International Annual Meetings (2019), ASA-CSSA-SSSA

[29] Salam A (2019) Subsurface mimo: A beamforming design in internet of underground things for digital agriculture applications. Journal of Sensor and Actuator Networks 8(3), DOI 10.3390/jsan8030041, URL `https://www.mdpi.com/2224-2708/8/3/41`

[30] Salam A (2019) Underground Environment Aware MIMO Design Using Transmit and Receive Beamforming in Internet of Underground Things, Springer International Publishing, Cham, pp 1–15

[31] Salam A (2019) An underground radio wave propagation prediction model for digital agriculture. Information 10(4):147

[32] Salam A (2019) Underground soil sensing using subsurface radio wave propagation. In: 5th Global Workshop on Proximal Soil Sensing, Columbia, MO

[33] Salam A (2020) Internet of Things for Environmental Sustainability and Climate Change, Springer International Publishing, Cham, pp 33–69. DOI 10.1007/978-3-030-35291-2_2, URL `https://doi.org/10.1007/978-3-030-35291-2_2`

[34] Salam A (2020) Internet of Things for Sustainability: Perspectives in Privacy, Cybersecurity, and Future Trends, Springer International Publishing, Cham, pp

299–327. DOI 10.1007/978-3-030-35291-2_10, URL https://doi.org/10.1007/978-3-030-35291-2_10
[35] Salam A (2020) Internet of Things for Sustainable Community Development, 1st edn. Springer Nature, DOI 10.1007/978-3-030-35291-2
[36] Salam A (2020) Internet of Things for Sustainable Community Development: Introduction and Overview, Springer International Publishing, Cham, pp 1–31. DOI 10.1007/978-3-030-35291-2_1, URL https://doi.org/10.1007/978-3-030-35291-2_1
[37] Salam A (2020) Internet of Things for Sustainable Forestry, Springer International Publishing, Cham, pp 147–181. DOI 10.1007/978-3-030-35291-2_5, URL https://doi.org/10.1007/978-3-030-35291-2_5
[38] Salam A (2020) Internet of Things for Sustainable Human Health, Springer International Publishing, Cham, pp 217–242. DOI 10.1007/978-3-030-35291-2_7, URL https://doi.org/10.1007/978-3-030-35291-2_7
[39] Salam A (2020) Internet of Things for Sustainable Mining, Springer International Publishing, Cham, pp 243–271. DOI 10.1007/978-3-030-35291-2_8, URL https://doi.org/10.1007/978-3-030-35291-2_8
[40] Salam A (2020) Internet of Things for Water Sustainability, Springer International Publishing, Cham, pp 113–145. DOI 10.1007/978-3-030-35291-2_4, URL https://doi.org/10.1007/978-3-030-35291-2_4
[41] Salam A (2020) Internet of Things in Agricultural Innovation and Security, Springer International Publishing, Cham, pp 71–112. DOI 10.1007/978-3-030-35291-2_3, URL https://doi.org/10.1007/978-3-030-35291-2_3
[42] Salam A (2020) Internet of Things in Sustainable Energy Systems, Springer International Publishing, Cham, pp 183–216. DOI 10.1007/978-3-030-35291-2_6, URL https://doi.org/10.1007/978-3-030-35291-2_6
[43] Salam A (2020) Internet of Things in Water Management and Treatment, Springer International Publishing, Cham, pp 273–298. DOI 10.1007/978-3-030-35291-2_9, URL https://doi.org/10.1007/978-3-030-35291-2_9
[44] Salam A (2020) Wireless underground communications in sewer and stormwater overflow monitoring: Radio waves through soil and asphalt medium. Information 11(2)
[45] Salam A, Karabiyik U (2019) A cooperative overlay approach at the physical layer of cognitive radio for digital agriculture
[46] Salam A, Shah S (2019) Internet of things in smart agriculture: Enabling technologies. In: 2019 IEEE 5th World Forum on Internet of Things (WF-IoT), IEEE, pp 692–695

[138] Salam A, Shah S (2019) Urban underground infrastructure monitoring IoT: the path loss analysis. In: 2019 IEEE 5th World Forum on Internet of Things (WF-IoT) (WF-IoT 2019), Limerick, Ireland
[139] Salam A, Vuran MC (2016) Impacts of soil type and moisture on the capacity of multi-carrier modulation in internet of underground things. In: Proc. ICCCN 2016, Waikoloa, Hawaii, USA
[47] Salam A, Vuran MC (2016) Impacts of soil type and moisture on the capacity of multi-carrier modulation in internet of underground things. In: Proc. of the 25th ICCCN 2016, Waikoloa, Hawaii, USA
[141] Salam A, Vuran MC (2017) Em-based wireless underground sensor networks. In: Pamukcu S, Cheng L (eds) Underground Sensing: Monitoring and hazard detection for environment and infrastructure - 1st edition, Elsevier, chap 5
[48] Salam A, Vuran MC (2017) Em-based wireless underground sensor networks pp 247–285, DOI 10.1016/B978-0-12-803139-1.00005-9
[49] Salam A, Vuran MC (2017) Smart underground antenna arrays: A soil moisture adaptive beamforming approach. In: Proc. IEEE INFOCOM 2017, Atlanta, USA
[50] Salam A, Vuran MC (2017) Wireless underground channel diversity reception with multiple antennas for internet of underground things. In: Proc. IEEE ICC 2017, Paris, France
[145] Salam A, Vuran MC, Irmak S (2016) Pulses in the sand: Impulse response analysis of wireless underground channel. In: Proc. IEEE INFOCOM 2016, San Francisco, USA
[51] Salam A, Vuran MC, Irmak S (2016) Pulses in the sand: Impulse response analysis of wireless underground channel. In: The 35th Annual IEEE International Conference on Computer Communications (INFOCOM 2016), San Francisco, USA
[147] Salam A, Vuran MC, Irmak S (2016) Pulses in the sand: Impulse response analysis of wireless underground channel. In: IEEE INFOCOM 2016-The 35th Annual IEEE International Conference on Computer Communications, IEEE, pp 1–9
[52] Salam A, Vuran MC, Irmak S (2017) Towards internet of underground things in smart lighting: A statistical model of wireless underground channel. In: Proc. 14th IEEE International Conference on Networking, Sensing and Control (IEEE ICNSC), Calabria, Italy
[53] Salam A, Hoang AD, Meghna A, Martin DR, Guzman G, Yoon YH, Carlson J, Kramer J, Yansi K, Kelly M, et al. (2019) The future of emerging iot paradigms: Architectures and technologies
[54] Salam A, Vuran MC, Dong X, Argyropoulos C, Irmak S (2019) A theoretical model of underground dipole antennas for communications in internet of underground things. IEEE Transactions on Antennas and Propagation
[55] Salam A, Vuran MC, Irmak S (2019) Di-sense: In situ real-time permittivity estimation and soil moisture sensing using wireless underground communications. Computer Networks 151:31 – 41, DOI https://doi.org/

10.1016/j.comnet.2019.01.001, URL http://www.sciencedirect.com/science/article/pii/S1389128618303141

[152] Saleh AA, Valenzuela R (1987) A statistical model for indoor multipath propagation. IEEE Journal on selected areas in communications 5(2):128–137

[153] Savazzi S, Spagnolini U, Goratti L, Molteni D, Latva-aho M, Nicoli M (2013) Ultra-wide band sensor networks in oil and gas explorations. IEEE Communications Magazine 51(4):150–160

[154] Schirrmann M, Gebbers R, Kramer E, Seidel J (2011) Soil ph mapping with an on-the-go sensor. Sensors 11(1):573–598

[155] Schroeder RJ (2002) The present and future of fiber optic sensors for the oilfield service industry: where is there a role? In: 2002 15th Optical Fiber Sensors Conference Technical Digest. OFS 2002 (Cat. No. 02EX533), IEEE, pp 39–42

[156] Shamma'a A, Tanner R, Shaw A, Lucas J (2003) On line em wave sand monitoring sensor for oil industry. In: Microwave Conference, 2003. 33rd European, IEEE, vol 2, pp 535–538

[157] Silva AR, Vuran MC (2009) Empirical evaluation of wireless underground-to-underground communication in wireless underground sensor networks. In: Proc. of IEEE DCOSS '09, Marina del Rey, CA, pp 231–244

[158] Silva AR, Vuran MC (2010) Communication with aboveground devices in wireless underground sensor networks: An empirical study. In: Proc. of IEEE ICC'10, Cape Town, South Africa, pp 1–6, DOI 10.1109/ICC.2010.5502315

[61] Silva AR, Vuran MC (2010) $(CPS)^2$: integration of center pivot systems with wireless underground sensor networks for autonomous precision agriculture. In: Proc. of ACM/IEEE International Conf. on Cyber-Physical Systems, Stockholm, Sweden, pp 79–88, DOI http://doi.acm.org/10.1145/1795194.1795206

[160] Skierucha W, Wilczek A (2010) A fdr sensor for measuring complex soil dielectric permittivity in the 10–500 mhz frequency range. Sensors 10(4):3314–3329

[161] Sojdehei JJ, Wrathall PN, Dinn DF (2001) Magneto-inductive (mi) communications. In: MTS/IEEE Oceans 2001. An Ocean Odyssey. Conference Proceedings (IEEE Cat. No. 01CH37295), IEEE, vol 1, pp 513–519

[162] Sudduth KA, Kitchen N, Bollero G, Bullock D, Wiebold W (2003) Comparison of electromagnetic induction and direct sensing of soil electrical conductivity. Agronomy Journal 95(3):472–482

[163] Sun L, Li Y (2010) Acoustic emission sound source localization for crack in the pipeline. In: 2010 Chinese Control and Decision Conference, IEEE, pp 4298–4301

[164] Sun Z, Akyildiz I (2010) Channel modeling and analysis for wireless networks in underground mines and road tunnels. IEEE Trans on Communications DOI 10.1109/TCOMM.2010.06.080353

[165] Sun Z, Akyildiz IF (2010) Channel modeling and analysis for wireless networks in underground mines and road tunnels. IEEE Transactions on communications 58(6):1758–1768

[166] Sun Z, Akyildiz IF (2013) Optimal deployment for magnetic induction-based wireless networks in challenged environments. IEEE transactions on wireless communications 12(3):996–1005

[167] Sun Z, Zhu B (2013) Channel and energy analysis on magnetic induction-based wireless sensor networks in oil reservoirs. In: 2013 IEEE International Conference on Communications (ICC), IEEE, pp 1748–1752

[168] Tan X, Sun Z, Akyildiz IF (2015) Wireless underground sensor networks: Mi-based communication systems for underground applications. IEEE Antennas and Propagation Magazine 57(4):74–87, DOI 10.1109/MAP.2015.2453917

[169] Tan X, Sun Z, Akyildiz IF (2015) Wireless underground sensor networks: Mi-based communication systems for underground applications. IEEE Antennas and Propagation Magazine 57(4):74–87

[170] Tan X, Sun Z, Akyildiz IF (2015) Wireless underground sensor networks: MI-based communication systems for underground applications. IEEE Antennas and Propagation Magazine 57(4), DOI 10.1109/MAP.2015.2453917

[65] Temel S, Vuran MC, Lunar MM, Zhao Z, Salam A, Faller RK, Stolle C (2018) Vehicle-to-barrier communication during real-world vehicle crash tests. Computer Communications 127:172–186

[172] Tenenbaum JB, De Silva V, Langford JC (2000) A global geometric framework for nonlinear dimensionality reduction. science 290(5500):2319–2323

[67] Tiusanen MJ (2006) Wideband antenna for underground Soil Scout transmission. IEEE Anten and Wireless Prop Ltrs

[104] Tiusanen MJ (2013) Soil scouts: Description and performance of single hop wireless underground sensor nodes. Ad Hoc Networks 11(5):1610 – 1618, DOI http://dx.doi.org/10.1016/j.adhoc.2013.02.002

[175] Vasisht D, Kapetanovic Z, Won J, Jin X, Sudarshan M, Stratman S (2020) Farmbeats: An iot platform for data-driven agriculture

[62] Vuran M, Dong X, Anthony D (2016) Antenna for wireless underground communication. US Patent 9,532,118

[177] Vuran MC, Akyildiz IF (2010) Channel model and analysis for wireless underground sensor networks in soil medium. Physical Communication 3(4):245–254, DOI DOI:10.1016/j.phycom.2010.07.001

[70] Vuran MC, Akyildiz IF (2010) Channel model and analysis for wireless underground sensor networks in soil medium. Physical communication 3(4):245–254

[111] Vuran MC, Salam A, Wong R, Irmak S (2018) Internet of underground things in precision agriculture: Architecture and technology aspects. Ad Hoc Networks 81:160–173

[71] Vuran MC, Salam A, Wong R, Irmak S (2018) Internet of underground things in precision agriculture: Architecture and technology aspects. Ad Hoc Networks DOI https://doi.org/10.1016/j.adhoc.2018.07.017, URL http://www.sciencedirect.com/science/article/pii/S1570870518305067

[72] Vuran MC, Salam A, Wong R, Irmak S (2018) Internet of underground things: Sensing and communications on the field for precision agriculture. In: 2018 IEEE 4th World Forum on Internet of Things (WF-IoT) (WF-IoT 2018), , Singapore

[182] Wang YPE, Lin X, Adhikary A, Grovlen A, Sui Y, Blankenship Y, Bergman J, Razaghi HS (2017) A primer on 3gpp narrowband internet of things. IEEE Communications Magazine 55(3):117–123

[183] Wark T, Corke P, Sikka P, Klingbeil L, Guo Y, Crossman C, Valencia P, Swain D, Bishop-Hurley G (2007) Transforming agriculture through pervasive wireless sensor networks. IEEE Pervasive Computing 6(2)

[184] Watson G (2006) Computing helmert transformations. Journal of computational and applied mathematics 197(2):387–394

[185] Wolfert S, Ge L, Verdouw C, Bogaardt MJ (2017) Big data in smart farming – a review. Agricultural Systems 153:69, DOI https://doi.org/10.1016/j.agsy.2017.01.023, URL http://www.sciencedirect.com/science/article/pii/S0308521X16303754

[186] Yan Q, Yang H, Vuran MC, Irmak S (2017) Spride: Scalable and private continual geo-distance evaluation for precision agriculture. In: IEEE Conference on Communications and Network Security (IEEE CNS), Las Vegas, NV, USA

[187] Yu X, Han W, Zhang Z (2017) Path loss estimation for wireless underground sensor network in agricultural application. Agricultural Research 6(1):97–102

[188] Zhang C, Kovacs JM (2012) The application of small unmanned aerial systems for precision agriculture: a review. Precision Agriculture 13(6):693–712, DOI 10.1007/s11119-012-9274-5, URL https://doi.org/10.1007/s11119-012-9274-5

[189] Zhang X, Andreyev A, Zumpf C, Negri MC, Guha S, Ghosh M (2017) Thoreau: A subterranean wireless sensing network for agriculture and the environment. In: 2017 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp 78–84, DOI 10.1109/INFCOMW.2017.8116356