1-2019

Di-Sense: In Situ Real-Time Permittivity Estimation and Soil Moisture Sensing using Wireless Underground Communications

Abdul Salam

Purdue University, salama@purdue.edu

Mehmet C. Vuran

University of Nebraska - Lincoln

Suat Irmak

University of Nebraska - Lincoln

Follow this and additional works at: https://docs.lib.purdue.edu/cit_articles

Salam, Abdul; Vuran, Mehmet C.; and Irmak, Suat, "Di-Sense: In Situ Real-Time Permittivity Estimation and Soil Moisture Sensing using Wireless Underground Communications" (2019). *Faculty Publications*. Paper 4.
https://docs.lib.purdue.edu/cit_articles/4

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.

Di-Sense: *In Situ* Real-Time Permittivity Estimation and Soil Moisture Sensing using Wireless Underground Communications

Abdul Salam

Environmental Networking Technology Laboratory, Department of Computer and Information Technology, Purdue University, USA

Mehmet C. Vuran

Cyber-Physical Networking Laboratory, Department of Computer Science and Engineering, University of Nebraska-Lincoln, Lincoln, NE

Suat Irmak

Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE 68583

Abstract

Internet of Underground Things (IOUT) communications have the potential for soil properties estimation and soil moisture monitoring. In this paper, a method has been developed for real-time *in situ* estimation of relative permittivity of soil, and soil moisture, that is determined from the propagation path loss, and velocity of wave propagation of an underground (UG) transmitter and receiver link in wireless underground communications (WUC). The permittivity and soil moisture estimation processes (*Di-Sense*, where *Di-* prefix means *two*) are modeled and validated through an outdoor UG software-defined radio (SDR) testbed, and indoor greenhouse testbed. SDR experiments are conducted in the frequency range of 100 MHz to 500 MHz, using antennas buried at 10 cm, 20 cm, 30 cm, and 40 cm depths in different soils under different soil moisture levels, by using dipole antennas with over the air (OTA) resonant frequency of 433 MHz. Experiments are conducted in silt loam, silty clay loam, and sandy soils. By using Di-Sense approach, soil moisture and permittivity can be measured with high accuracy in 1 m to 15 m distance range in plant root zone up to depth of 40 cm. The estimated soil parameters have less than 8% estimation error from the ground truth measurements and semi-empirical dielectric mixing models.

Keywords: Internet of Things, Wireless Underground Communications, Sensing, Precision Agriculture, Soil Moisture

1. Introduction

Internet of Underground Things (IOUT) have many applications in precision agriculture [1], [2], [4], [8], [13], [14], [15], [16], [17], [21], [35], [37], [48], [44], [53], [54], [64], [74], [79], Border monitoring is another important application area of IOUT, where these networks are being used to enforce border and stop infiltration [5], [61]. Monitoring applications of IOUT include land slide monitoring, and pipeline monitoring [3], [21], [30], [52], [59], [60], [73]. IOUT provides seamless access of information collected

from agricultural fields through the Internet. IOUT include in situ soil sensing capabilities (e.g., soil moisture, temperature, salinity), but also provide the ability to communicate through plants and soil, and real-time information about the environment (e.g., wind, rain, solar). When interconnected with existing machinery on the field (seeders, irrigation systems, combines), IOUT enable complete autonomy on the field, and pave the way for more efficient food production solutions. At agricultural farm level, IOUTs are being used to provide valuable information to the farmers.

Continuous sensing of soil moisture is essential for smart agriculture variable rate irrigation (VRI), real-time agricultural decision making, and water conservation [24]. Therefore, development of simple techniques to measure the in situ properties of soil is of vital importance. Moreover, permittivity estimation has applications in electromagnetic (EM) wave propagation analysis in the soil medium, depth analysis, subsurface imaging, and UG localization. Different methods for soil permittivity and moisture estimation are time-domain reflectometry (TDR) [40], [51], [66], ground-penetrating radar (GPR) mea-

*This document is the preprint version. The version of record is available at: Abdul Salam, Mehmet C. Vuran, Suat Irmak, Real-Time Permittivity Estimation and Soil Moisture Sensing using Wireless Underground Communications, *Computer Networks*, 2019 [1].

**Abdul Salam was with Cyber-Physical Networking Laboratory, Department of Computer Science and Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588 USA. He is now with Environmental Networking Technology Laboratory, Department of Computer and Information Technology, Purdue University, 47906 USA.

Email addresses: salama@purdue.edu (Abdul Salam), mcvuran@cse.unl.edu (Mehmet C. Vuran), sirmak2@unl.edu (Suat Irmak)

measurements [10], [23], [42], and remote sensing [27], [55], [67], [68]. Moreover, one major bottleneck in the current laboratory-based permittivity estimation techniques is off-line measurement of the collected soil samples. Remote sensing approaches are limited to shallow depths of 20 cm.

In situ measurements and inversion approach can be used to measure the soil properties at higher depths with greater accuracy. In this paper, we have developed Di-Sense, an in situ, real-time soil moisture and permittivity estimation approach based on the wireless underground communications (WUC) in IOUT. For a transmitting antenna in the soil, the generated electromagnetic (EM) waves propagate through the soil, and are not only affected by the depth, distance, frequency and soil moisture [49], but also depend on the properties of the soil [11]. Path loss of these attenuated waves received at the UG receiver can be used to deduce the properties of soil, and can also be used to estimate the soil moisture. Our approach to derive the soil moisture and relative permittivity is based on the path loss of the UG communications channel in IOUT. Path loss of transmitter-receiver (T-R) pair in WUC depends on distance, depth, and soil moisture. In Di-Sense, a transmitter antenna buried at a certain depth in soil transmits a wideband signal in frequency range of 100 MHz to 500 MHz, which propagates through the UG channel. The received signal is measured at the receiver to determine the path loss. Di-Sense enables an IOUT system to communicate simultaneously besides real-time permittivity estimation and soil moisture sensing. A model has been developed to estimate the soil moisture and permittivity based on path loss using Di-Sense. The model has been validated through experiments in a software-defined radio (SDR) testbed and in an indoor testbed in different soils at different depths under different soil moisture levels. Relative permittivity results show a very good agreement with less than 8 % estimation error from ground truth measurements, semi-empirical Peplinski dielectric mixing model [41], and Topp model [65].

The rest of the paper is organized as follows: The related work is discussed in Section 2. Di-Sense permittivity estimation and soil moisture sensing is modeled in Section 3. Model validation approaches are presented in Section 4. The description of empirical setup and measurements procedures is given in Section 5. Model validations and performance evaluations are performed in Section 6. Potential applications of the Di-Sense estimation approach are discussed in Section 7. Paper is concluded in Section 8.

2. Related Work

Different soil permittivity and moisture estimation approaches have historically been considered in the literature [9, 19, 36]. The following literature review is not all encompassing, rather we emphasize on some of the latest literature on the subject, with the purpose of highlighting similarities and differences with other works. Permittivity estimation and soil water measurement is classified

into different approaches. Methods used for quantifying soil water include gravimetric method, TDR, GPR, capacitance probes, remote sensing, hygrometric techniques, electromagnetic induction, tensionmetry, neutron thermalization, nuclear magnetic resonance, gamma ray attenuation, resistive sensors, and optical methods. Some of these methods are reviewed briefly in the following.

First, we discuss laboratory based soil properties estimation approaches. In [22], soil EM parameters are derived as function of soil moisture, soil density, and frequency. This model is restricted to 20 % soil moisture weight, and requires extensive sample preparation. In [11], a probe based laboratory equipment has been developed that requires use of vector network analyzer (VNA), and works in frequency range of 45 MHz to 26.5 GHz. A model based to estimate the dielectric permittivity of soil based on the empirical evaluation has been done in [75]. In [12], a model of dielectric properties of soil has been developed for frequencies higher than 1.4 MHz. In [41], Peplinski modified the model through extensive measurements to characterize the dielectric behavior of the soil in the frequency range of 300 MHz to 1.3 GHz. A comprehensive review of soil permittivity estimation approaches is given in [11]. These methods require the removal of the soil from the site. Moreover, laboratory based measurements of soil samples taken from site are labor-intensive, and are not truly representative of the in-situ soil conditions. Therefore, automated soil moisture monitoring technologies are needed.

Second approach to measure the soil properties, based on TDR, has been proposed in [40], that requires measurement of impedance and refractive index of soil. In [66], a method has been proposed to estimate the EM properties of soils for detection of Dense Non-Aqueous Phase Liquids (DNAPLs) hazardous materials using Cross-Well Radar (CWR). In this method, a wideband pulse waveform is transmitted in the frequency range of 0.5 GHz to 1.5 GHz, and soil permittivity is obtained using reflection and transmission simulations in dry sand. A detailed review of time domain permittivity measurements in soils is given in [69]. TDR based approach requires installation of sensors at each measurement location. However, real-time soil moisture sensing is required for effective decision making in agricultural fields.

Next, antenna based soil properties estimation approaches are discussed. In [56], [57], a method has been developed to measure the electrical properties of the earth using antennas buried in the geological media. However, this approach required adjustment of the length of antenna to achieve zero input reactance. This technique also requires measurement of the input reactance to derive the electrical constitutive parameters of the material. In [58], a GPR measurements based soil permittivity estimation is done in presence of soil antenna interactions by using the Fresnel reflection coefficients. However, only numerical results are presented without empirical validations, and this approach also requires complicated time-domain analysis. In [7], dielectric properties of the soil are measured

Figure 1: Estimation of soil properties using WUC.

in the frequency range of 0.1 GHz to 1 GHz using wide-band frequency domain method. This method requires use of impedance measurement equipment (LCR meter), and VNA. In [39], [77], a frequency domain method has been proposed to measure complex dielectric properties of the soil, that requires removing the soil and pacing it in a probe.

The GPR technique is also utilized to estimate soil permittivity and moisture. A method has been developed in [23] to estimate the permittivity of ground which is based on the correlation of the cross talk of early-time GPR signal with dielectric properties of ground. However, GPR method works for only shallow depth (0-20 cm), and requires a calibration procedure. Moreover, the depth resolution of soil moisture content measurement can not be restrained to a particular burial depth in soil.

Remote sensing of soil moisture is another important measurement approach. Although observation range is much higher with remote sensing [68], it is more sensitive to soil water content [27]. Passive remote sensing soil moisture measurement approaches [6], have very low spatial resolution (in the order of kilometers). Although, high spatial resolution is achieved (in the order of meters) with active sensing, however soil moisture measurement depth is restricted to the few top centimeters of the topsoil layers and vegetation cover effects the accuracy of soil moisture measurement [55].

From the review of soil moisture and permittivity measurement methods, it can be observed that there is a gap between the point based measurements, and large scale measurements. WUC have the potential to fill this gap for intermediate range (in the order of meters) spatial resolutions [33]. The main focus of this paper is on the use of WUC in permittivity estimation and soil moisture sensing. EM-wave communication in soil is impacted by soil properties and soil moisture [45], [49]. The presence and movement of even small amount of water results in significant changes in characteristics of the wireless UG channel between the sender and receiver nodes of an IOU communication system. Therefore, these changes can be identified by analysis of the path loss at the receiver. Main advantage of this approach is that field IOU infrastructure can be utilized for this purpose simultaneously by eliminating the need of specific soil moisture sensors. Hence, WUC

are effectively used for soil sensing purpose. Over the last decade, a significant progress in UG communications, UG channel modeling, and characterization of impact of soil type and moisture has been witnessed [2], [8], [17], [21], [37], [46], [49], [47], [50], [62], [64], [72], [70], [71]. A detailed characterization of the wireless UG channel has been provided in [49]. Impacts of soil type and moisture on the capacity of multi-carrier modulations are discussed in [45]. In this work, WUC are utilized by developing an approach to use the propagation path loss in IOU as soil sensing method, and is also validated through empirical measurements. We do not consider antenna impedance in our model and this remains outside the scope of the paper. This issue has been studied in our existing work, particularly we would like to draw attention of the reader to the reference [15] of the manuscript. Our work can be seen as a predecessor of wireless underground communications (WUC) measurement-based sensing techniques, as it provides an elegant modeling of the soil moisture and permittivity. This obviates the need of physical sensors in soil environment. Furthermore, WUC based sensing techniques will be tremendously important in emerging IOU applications with increasing needs of in situ sensing and communications. To the best of our knowledge, there exists no other technique for real-time in situ estimation of these properties based on WUC, and this is the first work that utilizes wireless UG channel path loss, and velocity of EM wave propagation in the UG channel to estimate soil moisture and permittivity.

3. System Models

To estimate the soil permittivity and moisture at a distance range of 1 m to 15 m, expressions are derived that connect these quantities to the measurable parameters of the WUC. For the permittivity estimation, these quantities are propagation path loss and velocity of wave propagation in soil. The problem to be investigated is framed as follows: given the path loss of communication link in the soil medium, derive a function that estimates the permittivity, and soil moisture of understudy soil medium. A schematic of WUC for soil relative permittivity estimation and soil moisture sensing is shown in Fig. 1. It is also important to note that the effective permittivity is equivalent to complex permittivity under low electrical loss. Moreover, in this paper, permittivity refers to the relative permittivity (real part of the complex dielectric constant). First, Di-Sense permittivity estimation using propagation path loss, and velocity of EM-wave propagation in soil is developed in Section 3.1, and then soil moisture model is presented in Section 3.2

3.1. Di-Sense Permittivity Estimation

Propagation Path Loss Approach: When EM wave communication is carried through the soil in IOU, the propagation loss due to the water molecules held in

Figure 2: (a) An example power delay profile (PDP) in the silt loam soil in the indoor testbed, (b) attenuation in soil as a function of operation frequency, (c) water-retention curve of the sandy soil, and silt loam soil, to convert soil matric potential (SMP) to volumetric water content (VWC) [25, 26], (d) the VWC-permittivity relationship by the Topp (soil independent) and Peplinski model (for three different soils).

Table 1: Empirical VWC range, depth, and particle size distribution and classification of testbed soils.

Textural Class	%Sand	%Silt	%Clay	VWC (%) Range	Depth
Silty Clay Loam - Greenhouse (SCL-G)	13	55	32	32 - 38	20 cm
Silt Loam - Field (SL-F)	17	55	28	22 - 38	10, 20, 30, and 40 cm
Sandy Soil - Indoor Testbed (S-I)	86	11	3	15 - 38	10, 20, 30, and 40 cm
Silt Loam - Indoor Testbed (SL-I)	33	51	16	30 - 37	10, 20, 30, and 40 cm

the soil medium, is function of the real effective permittivity (dielectric constant) of soil. Therefore, propagation path loss of the soil direct path (between the transmitter-receiver (T-R) pair) can be used to estimate the relative permittivity and soil moisture within 100 MHz-500 MHz range. To model soil permittivity, lowest path loss (LPL) across the whole frequency range is found by transmitting a known signal. The propagation path loss is determined by measuring the received signal. The transmitter transmits one signal using the narrow bandwidth at a time and frequency is increased sequentially in predefined step, Δf . Path loss is the ratio (expressed in decibel (dB)) of the transmitted power P_t to the power received P_r at the receiver. Path loss is determined as

$$PL = P_t - P_r = 10 \cdot \log_{10}(P_t/P_r), \quad (1)$$

where PL is the system path loss, and includes the effects of transmitting and receiving antenna gains G_t , and G_r , respectively. Once the path loss is measured, the frequency of the lowest path loss is determined by

$$f_{min} = F(\min(PL(f))), \quad (2)$$

where f_{min} is the frequency of the minimum pathloss. The f_{min} is not affected by distance between transmitter and receiver antennas, because of the antennas gains. Therefore, system path loss PL is inclusive of the antenna gains. Since PL measurements are done in narrowband, noise effects is minimal. Next the soil factor, ϕ , is calculated as:

$$\phi_s = f_{min}/f_0, \quad (3)$$

where f_0 is the resonant frequency of the antenna in the free space. Once the soil factor, ϕ_s , has been determined, the wavelength at the f_0 frequency is found

$$\lambda_0 = c/f_0, \quad (4)$$

where c is the speed of light. Accordingly, relative permittivity of the soil is determined as:

$$\epsilon_r = \frac{1}{(\phi_s \times \lambda_0)^2}. \quad (5)$$

Permittivity Estimation through Velocity of Wave Propagation in Soil: Due to the inhomogeneity of the soil medium, permittivity of the soil varies along the communication link from point to point. This leads to variations in wavelength and phase velocity, as the wave propagates in soil. Therefore, permittivity of the soil can be measured from the velocity of wave propagation soil. Power delay profile (PDP) are measured to get velocity of the wave propagation, that is determined from the known geometry layout of the testbed, by calculating the time that wave takes to reach at the receiver from transmitter. Once the velocity of the wave in soil, C_s , is determined relative permittivity in soil is calculated from the difference of transmission and arrival time of the direct component in the soil. Path of the direct component is completely through the soil. Accordingly, ϵ_r is determined as:

$$\epsilon_r = \left[C_s \times \frac{(\tau_{dr} - \tau_{dt})}{l} \right]^2, \quad (6)$$

where l is the distance between transmitter and receiver antennas, $\tau_{dr} - \tau_{dt}$ is travel time of the direct component in the soil, and C_s is the wave propagation velocity in soil. Due to different propagation velocities of the air and soil, direct wave is separate from the lateral wave which travels through the air along the soil-air interface, and has less attenuation as compared to the lateral wave [49]. In Fig. 2, an example power delay profile in the silt loam soil in the indoor testbed, and attenuation in soil as a function of operation frequency are shown.

Figure 3: Field testbed development in the silty loam soil: (a) testbed layout, (b) antenna placement, (c) outlook after antenna installation, (d) antenna cables out of soil at different depths, (e) USRPs and datalogger for soil moisture measurements.

Figure 4: (a) Power spectral density of the sent signal, (b) PSD of received signal at 50 cm distance at 225 MHz, (c) path loss vs. frequency at different burial depths.

3.2. Di-Sense Soil Moisture Sensing

The relationship of the soil moisture and permittivity is independent of the soil texture, bulk density, and frequency [65]. Since, soil permittivity depends on the soil moisture only, soil water content can be determined from soil permittivity [28], [65]¹. Since dry soil has relative permittivity of 3, and relative permittivity of the water is 80. Soil permittivity is calculated using (5) and (6), and accordingly, soil moisture is determined as [28], [65]:

$$VWC(\%) = \frac{\epsilon_r - 3}{.77} + 14.97. \quad (7)$$

4. Model Validation Techniques

To validate the model, ground truth measurements of soil water content are taken using the soil moisture sensors. Water content in soil is represented by two methods - soil matric potential, and volumetric water content (VWC). Soil matric potential is measured using the Watermark sensors buried at different depths. SMP is measured in centibars (CB)/kilopascals (kPa)². By using the soil-water retention curve [25], soil matric potential is converted to

¹Although, there is some error in soil moisture-permittivity relationship, and its dependence is also weak for mineral soils, it has been shown to work well in fine, and coarse textured soils [32].

²Greater matric potential values indicate lower soil moisture and zero matric potential represents near saturation condition, and 1 CB = 1 kPa.

soil volumetric water content. Water-retention curves of the sandy soil, and silt loam soil are shown in Fig. 2c. It can be observed that, in sandy soil, as compared to the silt loam soil, a small increase in SMP leads to significant decrease in VWC. This is caused by the large pore size in sandy soil [43]. Hence, it is important to develop soil specific water-retention curves, due to textural and water holding capacity differences within different soil types [26].

In addition to the ground truth measurements in testbed soils, model validation is also done with Topp, and Peplinski's dielectric mixing models to validate the Di-Sense model for different soil types under varying soil water content. Topp model [65] is not dependent on soil type, and it relates the soil permittivity to soil water content. Topp model is given as [65]:

$$\theta = 4.3 \times 10^{-6} \epsilon^3 - 5.5 \times 10^{-4} \epsilon^2 + 2.92 \times 10^{-2} \epsilon - 5.3 \times 10^{-2} \quad (8)$$

where θ is the soil water content, and ϵ is the dielectric constant of the soil.

The Peplinski model [41] is used to determine the dielectric constant of soil, which is expressed as $\gamma = \alpha + j\beta$ where

$$\alpha = \omega \sqrt{\frac{\mu \epsilon'}{2} \left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right]}, \quad (9)$$

$$\beta = \omega \sqrt{\frac{\mu \epsilon'}{2} \left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} + 1 \right]}, \quad (10)$$

where $\omega = 2\pi f$ is the angular frequency, μ is the magnetic

Figure 5: (a) Change in lowest path loss frequency of the UG channel at different soil moisture levels in sandy soil, silt loam, and silty clay loam soil, (b) Change in the lowest path frequency over depth, (c) Change in velocity of wave propagation as a function of soil moisture.

permeability, and ϵ' and ϵ'' are the real and imaginary parts of the dielectric constant as given in Appendix B. The VWC-permittivity relationship by the Topp (soil independent) and Peplinski model (for three different soils) is shown in Fig. 2d.

5. Empirical Setup

In this section, we describe the measurement setup and experiment methodology for model validation experiments. Development of outdoor software-defined radio (SDR) testbed, and measurements details are given in Section 5.1. Power delay profile (PDP) measurements are explained in Section 5.2. Empirical VWC range, burial depths, and particle size distribution and classification of testbed soils is given in Table 1. Soil name abbreviations are also given that are used in figures in rest of the paper for the purpose of brevity.

5.1. Outdoor/Field Software-Defined Radio (SDR) Testbed Development and Measurements

Testbed Development: The field testbed consists of four sets of buried dipole antennas in silt loam soil. Over-the-air resonant frequency of these dipole antennas is 433 MHz. Each set contains four antennas buried at 50 cm, 2 m, and 4 m distance from the first antenna, respectively. The antenna burial depths are 10 cm, 20 cm, 30 cm, and 40 cm. Testbed development steps are shown in Figs. 3, where the testbed layout is shown in Fig. 3a. Antenna placement, and outlook after antenna installation is shown in Fig. 3b-3c. In Fig. 3d, antenna cables out of soil at different depths are shown. An experiment with USRPs, and datalogger for soil moisture measurements is shown in Fig. 3e.

Experiment Methodology: The GNU Radio [20] and USRPs [18] are utilized to conduct SDR experiments in the field testbed. A Gaussian signal RF waveform of 2 MHz bandwidth is transmitted from an UG dipole antenna, buried at 40 cm depth, by using the transmitter USRP. Signal is received on the receiver USRPs, connected to dipole antennas buried at four different depths (e.g., 10

cm, 20 cm, 30 cm, and 40 cm), with a fixed transmitter-receiver distance of 50 cm. Experiment are repeated for all these depth for the distances of two meter and four meter. For each frequency, transmitter transmits for one second duration, and receivers collect IQ data of four mega samples. Receivers send an acknowledge to the transmitter after finishing the reception, and, accordingly, transmitter starts transmission at the next frequency. This process is repeated for frequency range of 100 MHz to 500 MHz for each depth and distance, and three measurements are taken. Post-processing is done in Matlab [38].

For spectral estimation and path loss analysis, Welch's method [78] is employed. This method is enhanced form of periodogram analysis. By using the computationally efficient Discrete Fourier Transforms, data is divided into fixed blocks to calculate periodograms, and modified periodograms. These modified periodogram are averaged to calculate the power spectrum. Details of periodogram method of power spectrum density (PSD) analysis are given in Appendix A. In Fig. 4a, PSD of the sent signal is shown.

In Fig. 4b, PSD of received signal at 50 cm distance for 10 cm, 20 cm, 30 cm, and 40 cm, depths is shown. Transmitters's burial depth is 40 cm. It is clearly evident that with increase in burial depth, PSD decreases significantly.

The pathloss with frequency at 10 cm, 20 cm, 30 cm, and 40 cm depths is shown in Fig. 4c. It can be observed that path loss increases significantly with frequency. This indicates that lower frequencies (e.g., less than 500 MHz) are more suitable for wireless UG channel in WUC.

5.2. PDP Measurements

In order to determine the velocity of EM wave propagation in soil, PDPs are measured by using the Keysight Technologies N9923A FieldFox VNA. PDP measurements are conducted in the indoor testbed, in sandy, and silt loam soils for dipole antennas buried at 10 cm, 20 cm, 30 cm, and 40 cm depths. Indoor testbed experiments are also done in sandy soil for different soil moisture levels. In the greenhouse testbed, in silty clay loam soil, an antenna is buried at 20 cm depth. Over-the-air resonant frequency

Figure 6: (a) Di-Sense VWC compared with ground truth VWC measurements, (b) Di-Sense VWC compared with Topp model (c) Di-Sense permittivity compared with Peplinski model (d) Di-Sense permittivity by time-domain velocity of propagation comparison with Di-Sense path loss propagation permittivity method.

Figure 7: Di-Sense error analysis: (a) Di-Sense VWC vs. ground truth VWC measurements, (b) Di-Sense VWC vs. Topp model (c) Di-Sense permittivity vs. Peplinski model (d) Di-Sense permittivity by time-domain velocity of propagation vs. Di-Sense path loss propagation permittivity method.

of these dipole antennas in all three soils is also 433 MHz. Channel transfer function and PDP measurement are conducted for different soil moisture levels. To measure PDP, a sinusoidal signal is transmitted by the VNA in frequency domain, from lower to higher frequencies, in an incremental step. The time-domain equivalent impulse response, $h(t)$, is produced from the frequency domain data by using the inverse Fourier transform (IFFT) operation. A total of 401 complex tones are stored in the frequency range of 10 MHz to 4 GHz. To suppress sidelobes, the windowing is done on the measured impulse response of the UG channel. Accordingly, velocity of wave propagation in soil is determined by the process described in Section 3.

6. Performance Analysis, Model Validation, and Error Analysis

In this section, first, propagation path loss has been measured for different soil types, under different soil moisture levels, at different burial depths using the methods described in Section 3. Impact of soil moisture, soil type, and burial depth variations on path loss are presented in Section 6.1. Model validation is carried out in Section 6.2. Model error analysis is done in Section 6.3.

6.1. Path Loss in Wireless Underground Communications

In Fig. 5a, change in lowest path loss frequency of the UG channel at different soil moisture levels is shown in sandy soil, silt loam, and silty clay loam soil. It is observed that, in sandy soil, with increase in soil moisture (15% to 36%), lowest path loss frequency has shifted 182

MHz lower from 321 MHz to 139 MHz, which is a 56% decrease. In silt loam soil, as soil moisture decrease from 38% to 22%, lowest path loss frequency has increased from 129 MHz to 207 MHz (60% increase). Similarly, in silty clay loam soil, with increase in soil moisture (32% to 38%), lowest path loss frequency has shifted 25 MHz lower from 160 MHz to 135 MHz, which is 15.62% decrease. In essence, in these soils, frequency of the lowest path loss decrease with increase in soil moisture, because of the fact that permittivity of soil is greater than the air, and it increases with increase in soil moisture, hence frequency of the lowest path loss shifts to the lower frequency end.

In Fig. 5b, change in the lowest path frequency over depth in silt loam, silty clay loam, and sandy soil is shown. From 10 cm depth to 20 cm depth, in silt loam soil, a change in lowest path loss frequency from 211 MHz to 201 MHz is observed, and at 40% depth, it has decreased to 185 MHz (which is a 12.32% less as compared to 10 cm depth). Whereas, in silt loam (field), from 10 cm to 40 cm depth, lowest path loss frequency is decreased by 38% from 197 MHz to 121 MHz. Similarly, in sandy soil, lowest path loss frequency, decreases from 308 MHz to 221 MHz when depth changes from 10 cm to 40 cm. This difference in lowest frequency with depth is caused by the reflected wave from the soil-air interface that induces a current on the antenna and changes the impedance which results in changes in lowest path loss frequency of the wireless UG channel. At higher depths, the distance to the soil-air interface is higher. Hence, the intensity of the reflected wave is less due to higher soil absorption. Furthermore, interaction of antenna fields with the soil causes changes

Figure 8: Di-Sense transfer functions: (a) soil permittivity, (b) soil permittivity time-domain (c) soil moisture.

in the lowest path loss frequency of the UG channel.

Moreover, it can also be observed that the change in lowest path loss frequency while going deep in sandy soil is much larger (27.10%) as compared to the 12.32% change in silt loam soil for the same depths. This happens because the relative permittivity of a particular soil depends on its net water content [12], and silt loam has a higher water holding capacity as compared to sandy soil. Therefore, silt loam has a higher relative permittivity, and results in a lower path loss frequency. Whereas sandy soil has low water holding capacity due to large number of pores that leads to lower permittivity, which shifts the lowest path loss frequency to higher spectrum.

In Fig. 5c, time of arrival of the the direct component is shown as a function of change in soil moisture. It can be observed that velocity of wave propagation in soil decrease with increase in soil moisture. In sandy soil, with VWC increase of 15% to 36%, wave velocity is decreased by five times. Similarly, in silty loam soil, it has decreased by three times, as soil moisture increases from 22% to 38%. It can also be observed silt loam has the 11% slower wave propagation velocity at 25% VWC as compared to sandy soil, because of the it higher relative permittivity.

6.2. Model Validation

In this section, model validation results are presented. The values of the soil moisture and soil permittivity, over soil moisture, are calculated accordingly by using the (5), (6) and (7), and results are shown in Figs. 6. In Figs. 6a-6b, Di-Sense VWC is compared with ground truth VWC measurements and Topp model. Di-Sense permittivity is compared with Peplinski model in Fig. 6c. Di-Sense permittivity by time-domain velocity of propagation method is also compared with Di-Sense path loss propagation permittivity method and results are shown in Fig. 6d.

While these graphs clearly show an excellent match of ground truth measurements and the models with Di-Sense, many interesting points are shown in Figs. 6. It can be observed that with decrease in lowest path loss frequency, soil permittivity increase rapidly, which also lead to increase in soil moisture. The Di-Sense model estimation error analysis is presented in the next section.

6.3. Model Error Analysis

Results of model error analysis are shown in Figs. 7. In Fig. 7a, Di-Sense VWC estimation error is shown with measured ground truth soil moisture sensing in different soils. Higher variability of Di-Sense soil moisture estimation error (1% - 8%) is in silt loam soil, and model error variations are less in sandy soil. This highlights the impact of clay contents in soil. Overall, estimation error is less than 8%.

Di-Sense soil moisture estimation error in comparison to the Topp model is shown in Fig. 7b. It can be observed that estimation error of Di-Sense as compared to the Topp model is also less than 7%, and higher variability of error is also observed in silt loam soil.

Di-Sense permittivity estimation error as compared to the Peplinski model is shown in Fig. 7c. It can be observed that Di-sense estimation error as compared to the Peplinski model is relatively high (21%) for silt loam (field) as compared to silty clay loam and silt loam (that has error less than 15%). It can also be seen that at higher soil moisture levels, less error is observed as compared to the lower soil moisture levels. Since many factors can affect the permittivity of water, at higher soil moisture level the relationship of soil medium dielectric constant becomes complicated. In addition, different factors (e.g., percentage of clay particles, soil temperature, soil type/texture, bulk density, salinity, porosity, soil bulk density) affect the soil permittivity. However, this effect is less significant on Di-Sense soil moisture estimation model, as still high accuracy in soil water content estimation is achieved in different soil types. Overall, these measured and modeled values are in agreement and the results show that Di-Sense method can be used to measure the soil permittivity and soil water content.

Moreover, it can also be seen that sandy soil permittivity is not compared with Peplinski model in Fig. 6c, because Peplinski model does not work with sandy soil with 86% sand content [41]. Differences in Di-Sense permittivity by time-domain velocity of propagation method with Di-Sense path loss propagation permittivity method are shown in Fig. 7d. Overall, both methods are in good

agreement for the testbed soils with less than 8% estimation differences. Therefore, the Di-Sense soil moisture and permittivity models can be used for soil moisture and permittivity estimation in soils that have similar particle size distribution and classification to those used in these experiments.

6.4. Di-Sense Transfer Functions

It is worth noting that the results presented here are intended for soil moisture and permittivity estimation, but these can also be used for IOUT communication system design. Moreover, effects of changes in soil permittivity with change in depth are likely to be reduced at higher depths due to the fact that intensity of the reflected wave from soil-air interface is reduced at the deeper depths. For estimation purpose, following procedure would be used:

- Determine the lowest path loss frequency.
- Estimate soil permittivity using (5) and (6).
- Estimate soil moisture using (7).

Di-Sense transfer functions of the soil permittivity and soil moisture are shown in Fig. 8. Soil moisture and permittivity of soil medium can be determined using these graphs from measured values of IOUT propagation path loss. Di-Sense measurement technique is simple and easy to use, and no knowledge of type of radios, communication parameters, and antennas, being used in IOUT deployment, is required, as long as propagation path loss can be measured accurately. Moreover, Di-Sense can also be used for different operation frequencies, f_0 , because (3), (4), scale accordingly with respect to the operation frequency. Like other measurement based techniques, there are some limitations for which the Di-Sense method is applicable. The major limitation is that propagation path loss of the soil under test should be measured accurately. For the application of Di-Sense to the application scenarios, where higher accuracy is required, an empirical factor can be used to account for the specific soil properties and soil-water retention capability.

7. Di-Sense Applications and Future Work

Di-Sense approach can be used in applications where a need arises for WUC. In precision agriculture, where IOUTs are already deployed [8], [13], [17], [31], [63], [76], the Di-Sense can be utilized for irrigation scheduling. Moreover, the health of growing plants can be assessed by detection in changes in root-zone soil moisture. It can also be further extended the soil macro-nutrient sensing for precision agriculture [29, 34].

In buildings and bridges structures, Di-Sense measurements can be used to determine the health of the these structures [36] by relating propagation path loss to properties of the communication medium. Di-Sense can also be used for detection of buried underground objects, where

the difference between the soil and object's relative permittivity can be used to identify the target and its properties and configuration. The use of higher frequencies in monitoring applications requires small antenna footprint because as the frequency is increased, the antenna length decreases accordingly.

Existing approaches to locate the underground landmines are impacted by the characteristics of the soil in which these landmines are buried. Di-Sense can be used to detect dynamic variations in the soil properties and can also improve the performance of landmines detection approaches.

The presence of high moisture content in mine tunnels can lead to fluctuations of permittivity of the tunnel walls and it can also affect the propagation of the EM waves within the tunnel and from tunnel to the ground link. In mine tunnels, Di-Sense can be used to improve the design of wave propagation systems for tunnels through cognitively adjusting the communication parameters based on the sensing of moisture and permittivity.

Another application of the Di-Sense is in the area of the geophysical prospecting, where IOUT can be used simultaneously for sensing, communications, and permittivity estimation of the ice and rocks. The contamination of soils can also be detected by the Di-Sense. It can also be used in meteorology, civil engineering, and geophysics.

From the implementation perspective, it is important to note that software-defined radio technology tends to need higher power for wide band spectrum scanning than the radios designed specifically for single band communication. However, the Di-Sense can be implemented effectively for a wide range of frequencies because it does not require advanced modulations schemes that require more power and are more complex.

8. Conclusions

In this paper, wireless UG channel path loss and velocity of wave propagation in soil medium has been utilized to determine the permittivity and soil moisture. Di-Sense is based on estimation of the frequency of the lowest path loss of the direct communication link between the buried antennas in soil. The soil properties estimated using models developed for different soils compare favorably with experimental and theoretically results presented in the literature, and with ground truth measurements. The Di-Sense models developed in this paper can be used for soil moisture and permittivity estimation in soils that have similar particle size distribution and classification to those used in these experiments. Di-Sense soil moisture and permittivity estimation approach accompanying fully-connected and reliable IOUT deployment in agricultural fields leads to improvements in precision agriculture practices.

9. Acknowledgments

This work is partially supported by a NSF CAREER award (CNS-0953900), NSF CNS-1423379, NSF CNS-1247941, CNS-1619285, and a NSF Cyber-Innovation for Sustainability Science and Engineering (CyberSEES) grant (DBI-1331895).

Appendix A. Periodogram Method of Power Spectrum Density

The collected data $X[n]$, $n=0, \dots, N-1$ is divided into K blocks. Length of these overlapping block is L , with a difference of D units from each other. Then,

$$\mathbf{X}_1(j) = X(j)j = 0, \dots, L-1. \quad (\text{A.1})$$

Similarly,

$$\mathbf{X}_2(j) = X(j+D)j = 0, \dots, L-1. \quad (\text{A.2})$$

and

$$\mathbf{X}_K(j) = X(j+(K-1)D)j = 0, \dots, L-1. \quad (\text{A.3})$$

For each L length block modified periodogram is calculated by selecting a data window $W(j)$ $j = 0, \dots, L-1$ in order to form the sequence $X_i(j)W(j), \dots, X_K W(j)$ Fourier transforms of these sequences $A_i(n), \dots, A_K(n)$ is taken as follows:-

$$\mathbf{A}_k(n) = \frac{1}{L} \sum_{j=0}^{L-1} X_k(j)W(j)e^{-2\pi i j n/L} \quad (\text{A.4})$$

where $i = (-1)^{\frac{1}{2}}$. K modified periodogram are obtained as following:-

$$\mathbf{I}_k(f_n) = \frac{L}{U} |A_k(n)|^2 \quad (\text{A.5})$$

where

$$f_n = \frac{n}{L} n = 0, \dots, L/2 \quad (\text{A.6})$$

and

$$U = \frac{1}{L} \sum_{j=0}^{L-1} W^2(j) \quad (\text{A.7})$$

Power spectral density (PSD) is the average of these periodogram and is given by [78]:-

$$\mathbf{P}(f_n) = \frac{1}{K} \sum_{k=0}^K I_k(f_n) \quad (\text{A.8})$$

Appendix B. Semi-Empirical Dielectric Mixing Model

The effective permittivity of soil-water mixture, which is a complex number, can be modeled as [41]:

$$\epsilon_s = \epsilon'_s - i\epsilon''_s, \quad (\text{B.1})$$

$$\epsilon'_s = \begin{cases} 1.15 \left[1 + \rho_b/\rho_s (\epsilon_s^\delta - 1) + (m_v)^{\nu'} (\epsilon'_{fw})^\delta - m_v \right]^{1/\delta} - 0.68 & 0.3 \text{ GHz} \leq f \leq 1.4 \text{ GHz} \\ \left[1 + \rho_b/\rho_s (\epsilon_s^\delta - 1) + (m_v)^{\nu'} (\epsilon'_{fw})^\delta - m_v \right]^{1/\delta} & 1.4 \text{ GHz} \leq f \leq 18 \text{ GHz} \end{cases} \quad (\text{B.2})$$

$$\epsilon''_s = \left[(m_v)^{\nu''} (\epsilon''_{fw})^\delta \right]^{1/\delta}, \quad (\text{B.3})$$

where f is the frequency in Hz, ϵ_s is the relative complex dielectric constant of the soil-water mixture, m_v is the volumetric water content, ρ_b is the bulk density and ρ_s is the particle density, δ , ν' and ν'' are empirically determined soil-type dependent constants given by

$$\delta = 0.65, \quad (\text{B.4})$$

$$\nu' = 1.2748 - 0.519S - 0.152C, \quad (\text{B.5})$$

$$\nu'' = 1.33797 - 0.603S - 0.166C, \quad (\text{B.6})$$

where S and C represent the mass fractions of sand and clay, respectively. The quantities ϵ'_{fw} and ϵ''_{fw} in (B.2) and (B.3) are the real and imaginary parts of the relative permittivity of free water, and are calculated from the Debye model [41]:

$$\epsilon'_{fw} = \epsilon_{w\infty} + \frac{\epsilon_{w0} - \epsilon_{w\infty}}{1 + (2\pi f \tau_w)^2}, \quad (\text{B.7})$$

$$\epsilon''_{fw} = \frac{2\pi f \tau_w (\epsilon_{w0} - \epsilon_{w\infty})}{1 + (2\pi f \tau_w)^2} + \frac{\delta_{eff}}{2\pi \epsilon_0 f} \frac{(\rho_s - \rho_b)}{\rho_s m_v}, \quad (\text{B.8})$$

where $\epsilon_{w\infty} = 4.9$ is the limit of ϵ'_{fw} when $f \rightarrow \infty$, ϵ_{w0} is the static dielectric constant for water, τ_w is the relaxation time for water, and ϵ_0 is the permittivity of free space. Expressions for τ_w and ϵ_{w0} are given as a function of temperature. At room temperature (20°C), $2\pi\tau_w = 0.58 \times 10^{-10}$ s and $\epsilon_{w0} = 80.1$. The effective conductivity, δ_{eff} , in (B.8) in terms of the textural properties of the soil, is given by

$$\delta_{eff} = \begin{cases} 0.0467 + 0.2204\rho_b - 0.4111S + 0.6614C & 0.3 \text{ GHz} \leq f \leq 1.4 \text{ GHz} \\ -1.645 + 1.939\rho_b - 2.25622S + 1.594C & 1.4 \text{ GHz} \leq f \leq 18 \text{ GHz} \end{cases} \quad (\text{B.9})$$

References

- [1] Abdul Salam, M. C. V. and Irmak, S. (2019). Real-time permittivity estimation and soil moisture sensing using wireless underground communications. *Computer Networks*.
- [2] Abrudan, T. E., Kypris, O., Trigoni, N., and Markham, A. (2016). Impact of rocks and minerals on underground magneto-inductive communication and localization. *IEEE Access*, 4:3999–4010.

- [3] Akkaş, M. A. (2017). Channel modeling of wireless sensor networks in oil. *Wireless Personal Communications*, pages 1–19.
- [4] Akyildiz, I. F. and Stuntebeck, E. P. (2006). Wireless underground sensor networks: Research challenges. *Ad Hoc Networks Journal*.
- [5] Akyildiz, I. F., Sun, Z., and Vuran, M. C. (2009). Signal propagation techniques for wireless underground communication networks. *Physical Communication Journal (Elsevier)*, 2(3):167–183.
- [6] b. Kim, S., Ouellette, J. D., van Zyl, J. J., and Johnson, J. T. (2016). Detection of inland open water surfaces using dual polarization l-band radar for the soil moisture active passive mission. *IEEE Transactions on Geoscience and Remote Sensing*, 54(6):3388–3399.
- [7] Bobrov, P., Repin, A., and Rodionova, O. (2015). Wideband frequency domain method of soil dielectric property measurements. *Geoscience and Remote Sensing, IEEE Transactions on*, 53(5):2366–2372.
- [8] Boga, H. R., Herbst, M., Huisman, J. A., Rosenbaum, U., Weuthen, A., and Vereecken, H. (2010). Potential of wireless sensor networks for measuring soil water content variability. *Vadose Zone Journal*.
- [9] Chang, K. (2005). *Encyclopedia of RF and Microwave Engineering*.
- [10] Comite, D., Galli, A., Lauro, S. E., Mattei, E., and Pettinelli, E. (2016). Analysis of gpr early-time signal features for the evaluation of soil permittivity through numerical and experimental surveys. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 9(1):178–187.
- [11] Curtis, J. O. (2001). A durable laboratory apparatus for the measurement of soil dielectric properties. *IEEE Transactions on Instrumentation and Measurement*, 50(5):1364–1369.
- [12] Dobson, M. and et.al. (1985). Microwave dielectric behavior of wet soil—Part II: Dielectric mixing models. *IEEE Trans. Geoscience and Remote Sensing*, GE-23(1):35–46.
- [13] Dong, X. and Vuran, M. C. (2010). Spatio-temporal soil moisture measurement with wireless underground sensor networks. In *Med-Hoc-Net '10*, Juan-les-pins, France.
- [14] Dong, X. and Vuran, M. C. (2011). A channel model for wireless underground sensor networks using lateral waves. In *Proc. of IEEE Globecom '11*, Houston, TX.
- [15] Dong, X. and Vuran, M. C. (2013a). Exploiting soil moisture information for adaptive error control in wireless underground sensor networks. In *2013 IEEE Global Communications Conference (GLOBECOM)*.
- [16] Dong, X. and Vuran, M. C. (2013b). Impacts of soil moisture on cognitive radio underground networks. In *Proc. IEEE Black-SeaCom*, Georgia.
- [17] Dong, X., Vuran, M. C., and 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.
- [18] Ettus Research Website.
- [19] Fishel, M., Koehn, P., and Rosen, E. (2014). Comparisons of ring resonator relative permittivity measurements to ground penetrating radar data. In *Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XIX*, volume 9072, page 90720O. International Society for Optics and Photonics.
- [20] GNU Radio Website.
- [21] Guo, H. and Sun, Z. (2014). Channel and energy modeling for self-contained wireless sensor networks in oil reservoirs. *IEEE Trans. Wireless Communications*, 13(4):2258–2269.
- [22] Hipp, J. E. (1974). Soil electromagnetic parameters as functions of frequency, soil density, and soil moisture. *Proceedings of the IEEE*, 62(1):98–103.
- [23] Hislop, G. (2015). Permittivity estimation using coupling of commercial ground penetrating radars. *IEEE Transactions on Geoscience and Remote Sensing*, 53(8):4157–4164.
- [24] Irmak, S. and et.al. (2012). Large scale on-farm implementation of soil moisture-based irrigation management strategies for increasing maize water productivity. *Transactions of the ASABE*, 55(3):881–894.
- [25] Irmak, S. and Haman, D. (2001). Performance of the watermark granular matrix sensor in sandy soils. *Applied Engineering in Agriculture*, 17(6):787.
- [26] Irmak, S. and Irmak, A. (2005). Performance of frequency-domain reflectometer, capacitance, and psuedo-transit time-based soil water content probes in four coarse-textured soils. *Applied engineering in agriculture*, 21(6):999–1008.
- [27] Jonard, F., Weihermüller, L., Schwank, M., Jadoon, K. Z., Vereecken, H., and Lambot, S. (2015). Estimation of hydraulic properties of a sandy soil using ground-based active and passive microwave remote sensing. *IEEE Transactions on Geoscience and Remote Sensing*, 53(6):3095–3109.
- [28] Josephson, B. and Blomquist, A. (1958). The influence of moisture in the ground, temperature and terrain on ground wave propagation in the vhf-band. *IRE Transactions on Antennas and Propagation*, 6(2):169–172.
- [29] Kim, H.-J., Sudduth, K. A., and Hummel, J. W. (2009). Soil macronutrient sensing for precision agriculture. *Journal of Environmental Monitoring*, 11(10):1810–1824.
- [30] Konda, A., Rau, A., Stoller, M. A., Taylor, J. M., Salam, A., Pribil, G. A., Argyropoulos, C., and Morin, S. A. Soft microreactors for the deposition of conductive metallic traces on planar, embossed, and curved surfaces. *Advanced Functional Materials*, 28(40):1803020.
- [31] Kukal, M. S. and 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.
- [32] Ledieu, J., Ridder, P. D., Clerck, P. D., and Dautrebande, S. (1986). A method of measuring soil moisture by time-domain reflectometry. *Journal of Hydrology*, 88(3):319–328.
- [33] Liedmann, F., Holewa, C., and Wietfeld, C. (2018). The radio field as a sensor - a segmentation based soil moisture sensing approach. In *2018 IEEE Sensors Applications Symposium (SAS)*, pages 1–6.
- [34] Lin, J., Wang, M., Zhang, M., Zhang, Y., and Chen, L. (2007). Electrochemical sensors for soil nutrient detection: Opportunity and challenge. In *International Conference on Computer and Computing Technologies in Agriculture*, pages 1349–1353. Springer.
- [35] Liu, G., Wang, Z., and Jiang, T. (2016). Qos-aware throughput maximization in wireless powered underground sensor networks. *IEEE Transactions on Communications*, 64(11):4776–4789.
- [36] Liu, H. and Sato, M. (2014). In situ measurement of pavement thickness and dielectric permittivity by gpr using an antenna array. *Ndt & E International*, 64:65–71.
- [37] Markham, A. and Trigoni, N. (2012). Magneto-inductive networked rescue system (miners): Taking sensor networks underground. In *Proceedings of the 11th ICPS, IPSN '12*, pages 317–328. ACM.
- [38] MATLAB.
- [39] Nassar, E. M., Lee, R., and Young, J. D. (1999). A probe antenna for in situ measurement of the complex dielectric constant of materials. *IEEE Transactions on Antennas and Propagation*, 47(6):1085–1093.
- [40] Nicolson, A. M. and Ross, G. F. (1970). Measurement of the intrinsic properties of materials by time-domain techniques. *IEEE Transactions on Instrumentation and Measurement*, 19:377–382.
- [41] Peplinski, N., Ulaby, F., and Dobson, M. (1995). Dielectric properties of soil in the 0.3–1.3 ghz range. *IEEE Transactions on Geoscience and Remote Sensing*, 33(3):803–807.
- [42] Pettinelli, E., Matteo, A. D., Mattei, E., Crocco, L., Soldovieri, F., Redman, J. D., and Annan, A. P. (2009). Gpr response from buried pipes: Measurement on field site and tomographic reconstructions. *IEEE Transactions on Geoscience and Remote Sensing*, 47:2639–2645.
- [43] S. Irmak, J.O. Payero, D. E. W. K. D. M. G. Z. J. R. B. V. A. C. and Leininger, D. (2006). Watermark granular matrix sensor to measure soil matric potential for irrigation management. Technical Report EC783, University of Nebraska-Lincoln Extension Circular.

- [44] 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).
- [45] Salam, A. and Vuran, M. C. (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.
- [46] Salam, A. and Vuran, M. C. (2017a). Smart underground antenna arrays: A soil moisture adaptive beamforming approach. In *Proc. IEEE INFOCOM 2017*, Atlanta, USA.
- [47] Salam, A. and Vuran, M. C. (2017b). Wireless underground channel diversity reception with multiple antennas for internet of underground things. In *Proc. IEEE ICC 2017*, Paris, France.
- [48] Salam, A. and Vuran, M. C. (2018). Em-based wireless underground sensor networks. In Pamukcu, S. and Cheng, L., editors, *Underground Sensing*, pages 247 – 285. Academic Press.
- [49] Salam, A., Vuran, M. C., and Irmak, S. (2016). Pulses in the sand: Impulse response analysis of wireless underground channel. In *Proc. IEEE INFOCOM 2016*, San Francisco, USA.
- [50] Salam, A., Vuran, M. C., and 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.
- [51] Scott, W. R. and Smith, G. S. (1992). Measured electrical constitutive parameters of soil as functions of frequency and moisture content. *IEEE Transactions on Geoscience and Remote Sensing*, 30(3):621–623.
- [52] Shamma'a, A., Tanner, R., Shaw, A., and Lucas, J. (2003). On line em wave sand monitoring sensor for oil industry. In *Microwave Conference, 2003. 33rd European*, volume 2, pages 535–538. IEEE.
- [53] Silva, A. R. and Vuran, M. C. (2010a). (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*, pages 79–88, Stockholm, Sweden.
- [54] Silva, A. R. and Vuran, M. C. (2010b). Development of a Testbed for Wireless Underground Sensor Networks. *EURASIP Journal on Wireless Communications and Networking*, 2010.
- [55] Small, E. E., Larson, K. M., Chew, C. C., Dong, J., and Ochsner, T. E. (2016). Validation of gps-ir soil moisture retrievals: Comparison of different algorithms to remove vegetation effects. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 9(10):4759–4770.
- [56] Smith, G. and Nordgard, J. (1985). Measurement of the electrical constitutive parameters of materials using antennas. *IEEE Transactions on Antennas and Propagation*, 33(7):783–792.
- [57] Smith, G. S. and King, R. W. P. (1974). The resonant linear antenna as a probe for measuring the in situ electrical properties of geological media. *Journal of Geophysical Research*, 79(17):2623–2628.
- [58] Solimene, R., D'Alterio, A., Gennarelli, G., and Soldovieri, F. (2014). Estimation of soil permittivity in presence of antenna-soil interactions. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 7(3):805–812.
- [59] Sun, Z. and Akyildiz, I. (2010). Channel modeling and analysis for wireless networks in underground mines and road tunnels. *IEEE Trans. on Communications*.
- [60] Sun, Z. and et.al. (2011). MISE-PIPE: MI based wireless sensor networks for underground pipeline monitoring. *Ad Hoc Networks*.
- [61] Sun, Z., Wang, P., Vuran, M. C., Al-Rodhaan, M. A., Al-Dhelaan, A. M., and Akyildiz, I. F. (2011). Border patrol through advanced wireless sensor networks. *Ad Hoc Networks*, 9(3):468–477.
- [62] Tan, X., Sun, Z., and Akyildiz, I. F. (2015). Wireless underground sensor networks: MI-based communication systems for underground applications. *IEEE Antennas and Propagation Magazine*, 57(4).
- [63] Tiisanen, M. J. (2006). Wideband antenna for underground Soil Scout transmission. *IEEE Antennas and Wireless Propagation Letters*, 5(1):517–519.
- [64] Tiisanen, M. J. (2013). Soil scouts: Description and performance of single hop wireless underground sensor nodes. *Ad Hoc Networks*, 11(5):1610 – 1618.
- [65] Topp, G. C., Davis, J. L., and Annan, A. P. (1980). Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research*, 16(3):574–582.
- [66] Toro-Vazquez, J., Rodriguez-Solis, R. A., and Padilla, I. (2012). Estimation of electromagnetic properties in soil testbeds using frequency and time domain modeling. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 5(3):984–989.
- [67] Ulaby, F. T. and Long, D. G. (2014). *Microwave Radar and Radiometric Remote Sensing*. University of Michigan Press.
- [68] van der Velde, R., Salama, M. S., Eweys, O. A., Wen, J., and Wang, Q. (2015). Soil moisture mapping using combined active/passive microwave observations over the east of the netherlands. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 8(9):4355–4372.
- [69] Vereecken, H., Schnepf, A., Hopmans, J. W., Javaux, M., Or, D., Roose, T., Vanderborght, J., Young, M., Amelung, W., Aitkenhead, M., et al. (2016). Modeling soil processes: Review, key challenges, and new perspectives. *Vadose Zone Journal*, 15(5).
- [70] Vuran, M. and Akyildiz, I. (2008). Cross-layer packet size optimization for wireless terrestrial, underwater, and underground sensor networks. In *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, pages 226 –230.
- [71] Vuran, M. C. and Akyildiz, I. F. (2010). Channel model and analysis for wireless underground sensor networks in soil medium. *Physical Communication*, 3(4):245–254.
- [72] Vuran, M. C., Dong, X., and Anthony, D. (2016). Antenna for wireless underground communication. US Patent 9,532,118 B2.
- [73] Vuran, M. C., Salam, A., Wong, R., and Irmak, S. (2018a). Internet of underground things in precision agriculture: Architecture and technology aspects. *Ad Hoc Networks*, 81:160 – 173.
- [74] Vuran, M. C., Salam, A., Wong, R., and Irmak, S. (2018b). 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.
- [75] Wang, J. R. and Schmugge, T. J. (1980). An empirical model for the complex dielectric permittivity of soils as a function of water content. *IEEE Transactions on Geoscience and Remote Sensing*, GE-18(4):288–295.
- [76] Wark, T., Corke, P., Sikka, P., Klingbeil, L., Guo, Y., Crossman, C., Valencia, P., Swain, D., and Bishop-Hurley, G. (2007). Transforming agriculture through pervasive wireless sensor networks. *IEEE Pervasive Computing*, 6(2).
- [77] Weir, W. B. (1974). Automatic measurement of complex dielectric constant and permeability at microwave frequencies. *Proceedings of the IEEE*, 62(1):33–36.
- [78] Welch, P. D. (1967). The use of fast fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. *Audio and Electroacoustics, IEEE Transactions on*, 15(2):70–73.
- [79] Zhang, X., Andreyev, A., Zumpf, C., Negri, M. C., Guha, S., and Ghosh, M. (2017). Thoreau: A subterranean wireless sensing network for agriculture and the environment. In *Computer Communications Workshops (INFOCOM WKSHPS), 2017 IEEE Conference on*, pages 78–84. IEEE.

Abdul Salam (salama@purdue.edu) is an Assistant Professor in the Department of Computer and Information Technology at the Purdue University. His research involves wireless underground sensor networks, underground channel modeling, capacity analysis, and network protocols. He received his B.Sc. and MS degrees in Computer Sciences from Bahauddin Zakariya University, Multan, Pakistan in 2001 and 2004, respectively; and MS in Computer Engineering from UET, Taxila, Pakistan in 2012. He received his Ph.D. degree in Computer Engineering from the Cyber-Physical Networking Laboratory, Department of Computer Science and Engineering, University of Nebraska-Lincoln, Lincoln, NE, in 2018, under the guidance of Prof. Mehmet C. Vuran.

Abdul Salam has served in the Pakistan Army for 9 years in a number of command, staff, and field roles. He held the Principal position at the Army Public School and College, Thal Cantonment. Prior to his service at Pakistan Military, he was a lecturer at Department of Computer Science, Bahauddin Zakariya University, Multan; and Department of Computer Science and Information Technology, Islamia University, Bahawalpur, Pakistan. He is the recipient of ICCCN 2016 Best Student Paper Award, Robert B. Daugherty Water for Food Institute Student Fellowship, Gold Medal MS (CS) on securing first position in order of merit, and 2016-2017 Outstanding Graduate Student Research Award from Department of Computer Science and Engineering (CSE), University of Nebraska-Lincoln. Dr. Abdul Salam directs the Environmental Networking Technology (ENT) laboratory. He is the member of the Realizing the Digital Enterprise (RDE) research group and Center for Environment (C4E), a Purdue's initiative for interdisciplinary, problem-driven research and teaching.

Mehmet C. Vuran (mcvuran@cse.unl.edu) received his B.Sc. degree in Electrical and Electronics Engineering from Bilkent University, Ankara, Turkey, in 2002. He received his M.S. and Ph.D. degrees in Electrical and Computer Engineering from

the Georgia Institute of Technology, Atlanta, in 2004 and 2007, respectively, under the guidance of Prof. Ian F. Akyildiz. Currently, he is the Susan J. Rosowski Associate Professor of Computer Science and Engineering at the University of Nebraska-Lincoln and Robert B. Daugherty Water for Food Institute Fellow. He was awarded the Thomson Reuters Highly Cited Researcher award in 2014, and 2015. He is the recipient of an NSF CAREER award in 2010 and the co-author of Wireless Sensor Networks textbook. His current research interests include wireless underground communications, cognitive radio networks, cross-layer design, and correlation-based communication. He is an Associate Editor of IEEE Transactions on Wireless Communications, Computer Networks Journal (Elsevier) and IEEE Communications Surveys and Tutorials.

Suat Irmak has a doctorate in agricultural and biological engineering from the University of Florida. He holds leadership roles in the American Society of Civil Engineers-Environmental and Water Resources Institute, for which he chairs the Evapotranspiration in Irrigation Hydrology Committee; American Society of Agricultural and Biological Engineers (ASABE); United States Committee on Irrigation and Drainage; and others. He has earned numerous awards and honors, including the ASABE New Holland Young Researcher Award and the ASABE Young Extension Worker Award.

Suat Irmak's research, extension and educational programs apply engineering and scientific fundamentals in soil and water resources engineering, irrigation engineering and agricultural water management, crop water productivity, evapotranspiration and other surface energy fluxes for agro-ecosystems; invasive plant species water use; and impacts of changes in climate variables on water resources and agro-ecosystem productivity. Irmak leads the Nebraska Agricultural Water Management Network, which aims to increase adoption of new tools, technologies and strategies for increasing crop water productivity and reducing energy use in agriculture. He established the Nebraska Water and Energy Flux Measurement, Modeling and Research Network, made up of 12 water- and surface-energy flux towers forming a comprehensive network that measures surface energy and water vapor fluxes, micro-climatic variables, plant physiological parameters and biophysical properties, water use efficiency, soil water content, surface characteristics and their interactions for various agro-ecosystems.