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Underground Soil Sensing Using Subsurface Radio Wave Propagation

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Abstract

Continuous sensing of soil moisture is essential for smart agriculture variable rate irrigation (VRI), real-time agricultural decision making, and water conservation. 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), ground-penetrating radar (GPR) measurements, and remote sensing. One major bottleneck in the current laboratory-based permittivity estimation techniques is off-line measurement of the collected soil samples. At that, the remote sensing approaches are limited to shallow depths of 20cm.

Internet of Underground Things (IOUT) communications have the potential for soil properties estimation and soil moisture monitoring. 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 100MHz to 500MHz, using antennas buried at 10cm, 20cm, 30cm, and 40cm depths in different soils under different soil moisture levels, by using dipole antennas with over the air (OTA) resonant frequency of 433MHz. 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 1m to 15m distance range in plant root zone up to depth of 40cm. The estimated soil parameters have less than 8% estimation error from the ground truth measurements and semi-empirical dielectric mixing models.

Introduction

Our telluric ecosystem, a lifeline of our essential provisions and economic well-being, is based on soil. It contains multitude of organisms which, through their physical, biological, and chemical processes, provide a cogent environment and nutrients required for food production and plant growth. The soil ecosystem regulates the circulation of Earth and environmental substances. It is also home to antibiotics that are used to cure diseases and store gases (e.g., methane, carbon dioxide, and oxygen) essential for life on our planet. Therefore, to meet the food needs of increasing population of World, enhanced understanding of the soil ecosystem is required (Salam et al., 2016).

By 2020, Cisco's visual networking index expects that 11.6 billion devices will be connected to the Internet. This number is greater than the projected population of the World (10 billion by 2050). The data insights from these devices will carry a $11 trillion economic value. There is a need for innovation in a diverse set of precision agriculture areas, particularly in underground soil sensing. From an era where only tractors, seeders, combines, harvesters, and farm machinery were used with very limited technology, we are foreseeing a future in which computing, and information technologies will be integral to every piece of equipment on the field. Growers will routinely use computers that are millions of times more powerful, connected to the Cloud with ubiquitous availability of data and information, and have communication capability with the underground equipment through increasingly sophisticated interfaces. Many billions of data points are already being generated on daily basis at large farms. Virtually every agricultural area has been profoundly impacted by advances in computing technologies. Despite their recent impact in more effective water management decision-making, advanced automated and wireless soil sensing technologies still face practical application challenges. More specifically, lack of robust rural wireless service, difficulty of installing and removing soil moisture sensors before and after a growing season, and overall mistrust to information systems due to privacy concerns, limit their adoption. Therefore, wireless communications-based soil sensing devices imbedded permanently in the soil, coupled with secure, privacy-preserving, and robust wireless underground network infrastructure in rural agricultural communities, will significantly contribute to the adoption of technology in production fields.

An improvement of up to 40% improvement in water use efficiency is possible if an in-situ soil moisture measurement sensors-based approach is used for variable rate irrigation in the field of precision agriculture. The process of installing and removing sensors is laborious and time consuming. Thus, permanently installed sensors can enhance the technology implementation in fields. Moreover, autonomous irrigation can reduce human error in decision-making. It also eliminates over- or under-irrigation and further enhances water use efficiency. This project aims to develop technology to address the data acquisition challenges in soil moisture monitoring. Existing water content monitoring in the field of precision agriculture is enabled by satellite data services, that leads to higher cost and data rates are also very low. Current practices in soil moisture monitoring techniques use soil moisture sensors that provide readings at depths of 4 inches and use capacitive and resistive methods. Weather stations contain rain fall, temperature, humidity, and pressure sensors. These base and weather stations are also wired to sensors. All major irrigation companies use sensors which are wired to data loggers. Through the proposed underground novel soil sensing systems, the soil moisture monitoring can be done in the crop fields at a lower cost, with higher data rates in large-scale farms.

The IOUT represents autonomous devices that collect any relevant information about the Earth and are interconnected with communication and networking solutions that facilitate sending the information out of fields to the growers and decision mechanisms. These novel approaches have broadened the scope of existing applications and have the potential to enable a wide array of novel solutions from saving water resources for more food production to improving crop yields by smart irrigation. Internet of things (IoT) devices that bridge and advance both cyber-engineering and the physical world will be a key area of opportunity in the next decade. The emerging use of IOUT in many areas, including precision agriculture, transportation, environment and infrastructure monitoring, and border patrol, underscores the importance of wireless underground communications. The PI’s research program aims to address problems that require theoretical modeling and empirical validations coupled with simulations to get physical insights into the propagation of radio waves in stratified medium.

We have captured and analyzed the *impulse response* of the wireless UG channel through extensive experiments (Salam et al., 2016, April). A statistical model for the wireless UG channel based on these empirical evaluations has also been developed. The *statistical model* is based on the analysis of the properties of the power delay profiles measured in different soils under different water content levels in the indoor testbed and field settings. By using the impulse response analysis, a *soil moisture based multi-carrier modulation* scheme (Salam et al., 2016, August) has been developed for high data-rate communications. Moreover, the insights gained from radio wave propagation in soil are utilized for to develop a novel design of a *soil moisture adaptive beamforming approach* (SMABF) for long range communications (Salam et al., 2017, May). A novel framework for UG beamforming using adaptive antenna arrays are presented to extend communication distances for practical applications. Furthermore, we investigated the performance and directivity improvements by employing spatial diversity at the receiver through experiments and a *Lateral-Direct-Reflected (LDR)* approach to exploit the spatial diversity in the UG wireless channel by using multiple antennas (Salam et al., 2017, May). A theoretical model to investigate the impact on change of soil moisture on the performance of a dipole antennas buried underground has been developed (Salam et al., 2019).

The insights gathered from the experimental and theoretical work clearly show that the there exists a relationship between the wireless UG communications and soil processes. Based on the findings and analysis of this empirical work (Salam and Vuran, 2016, 2017 May; 2017 May; 2017 August), five types of soil physical processes have been identified that have a significant impact on the radio wave propagation in the soil medium. The analysis of those processes analyses of those will lead to development of novel underground sensing systems and is also be the novel contribution of this proposed work: (1) **Soil Type and Density Impacts:** The attenuation of the radio waves propagating in the stratified medium is higher as compared to over-the-air (OTA) medium. The soil type and bulk soil density contributes to this loss because of the pore size and water holding capacity differences among different soils. (2) **Volumetric Water Content Impacts:** The radio wave propagation exhibits additional loss which comes from an extra attenuation induced by absorption of these waves through volumetric water content. Therefore, in addition to the diffusion attenuation, the complex permittivity of the soil leads to additional path loss in soil medium. (3) **Distance and Depth Impacts:** A soil profile is divided into multiple horizons. Sensing devices for precision agriculture are usually buried in the O and A horizon of the soil profile. Therefore, the depth and distance between the sensing devices affects the path loss between the sender and receiver antennas. The air-soil interface also causes reflection on the buried antennas. (4) **Antenna Impacts:** The return loss of the underground antenna is not the same as the OTA, because the permittivity of soil impacts the return loss. Therefore, the resonant frequency shifts with change in soil moisture. With shift in resonant frequency the operation frequency needs to be adjusted for maximum communication efficiency. (5) **Frequency Impacts:** The radio wave path loss attenuation in soil also depends on the operation frequency. The choice of the operation frequency effects the maximum achievable capacity in the wireless underground communications. Moreover, the selection of the antenna requires consideration of the operation frequency.

Therefore, in the design for wireless underground communications based underground soil sensing systems, these soil processes need to be considered such that the accurate models of the soil physical phenomena can be devised according to changes in environmental conditions. Finally, the feasibility of UG soil sensing systems depend on the investigation and accurate measurements of multiple novel parameters not considered for traditional over-the-air (OTA) communications. For instance, such sensing paradigm must be robust to variations in soil's physical parameters, such as abrupt changes in soil profile layers, and volumetric water content variations across multiple layers. To this end, a new generation of advanced soil system has been developed. The aim of this work is to develop a novel underground soil system for sensing of different physical, biological, and chemical properties of the soil with the ability to sense according to its surrounding in different soil types. The development of such sensing system will also pave the way for novel precision agriculture applications that have not been perceived yet through improved understanding if soil properties. It will also aid in advancing the fields of subsurface radio wave propagation, underground communications and networking, and precision agriculture data analytics. This novel way of studying soil properties will facilitate efficient resource usage (e.g., improved water conservation, improved crop yield) leading to healthy and sustainable communities.

Background and Related Work

The Internet of Underground Things (IOUT) are being used in many areas including environment and infrastructure monitoring precision agriculture contaminated soil and dense nonaqueous phase liquids (DNAPLs) detection, detection of buried objects, and ground penetrating radars. Underground communications is an emerging field and lacks well established and empirically validated channel models. Over the air (OTA) channel models cannot be directly applied to UG communications because UG medium is lossy and is affected by soil, air, and moisture. These factors leads to diverse soils dielectric spectra based on time, frequency, and space. Electromagnetic (EM)-based wireless communication in UG channel is affected by different factors. These factors include soil type, soil moisture, operation frequency, transmitter-receiver (T-R) distances, and depth. All these factors must be taken into consideration for accurate path loss modeling. Underground (UG) channel path loss models have been developed in using theoretical electromagnetic fields analysis. However, these channel models have not been verified through experimentation. Therefore, empirical evaluations and validations are necessary to characterize the effects of operation frequency, soil moisture, soil texture, burial depth, and distance on the UG communications. Furthermore, performance of the UG antenna also needs to be analyzed. Moreover, deeper understanding of the effects of soil-air interface, dielectric properties of the soil, and lateral wave can also be realized through an extensive experimentation campaign. The development of a wireless underground channel path loss model that accounts for the soil type and moisture impact is important because of many factors such as the operation frequency, communications protocol, modulation scheme, network layout, connectivity and other important operational parameters can be ascertained based on the model. Moreover, to evaluate IOUT solutions, a reliable UG channel model is required. Existing over-the-air (OTA) channel models cannot be used in subsurface communications because of the high path loss that is caused by complex permittivity of the soil in the lossy propagation medium. Moreover, spatial and temporal changes in the soil permittivity also lead to path loss variations, a phenomena not observed in OTA communications.

There are three different paths that contribute to propagation in wireless underground communications. Through-the-soil paths are direct and reflected. For both components, the wave path remains completely in the soil. The third wave, lateral component, moves along the air-soil interface above the soil surface. An in-depth discussion of these components of UG channel is presented in (Vuran et.al, 2018).

System Model

To estimate the soil permittivity and moisture at a distance range of 1–15 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. 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).

When EM wave communication is carried through the soil in IOUT, the propagation loss due to the water molecules held in the soil medium, is function of the real effective permittivity (dialectic 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 100–500 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

$$PL = P_t - P_r = 10.\ \log 10(P_t / P_r), \tag{1}$$

where PL is the system path loss, and it 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.

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

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:

$$\varphi_s = f_{min} / f_0, \tag{3}$$

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:

$$\lambda_0 = c / f_0, \tag{4}$$

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

$$\varepsilon_r = 1 / (\varphi_s \times \lambda_0)^2 . \tag{5}$$

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. ε_r is determined as:

$$\varepsilon_r = [C_s \times (\tau_{dr} - \tau_{dt})/l], \tag{6}$$

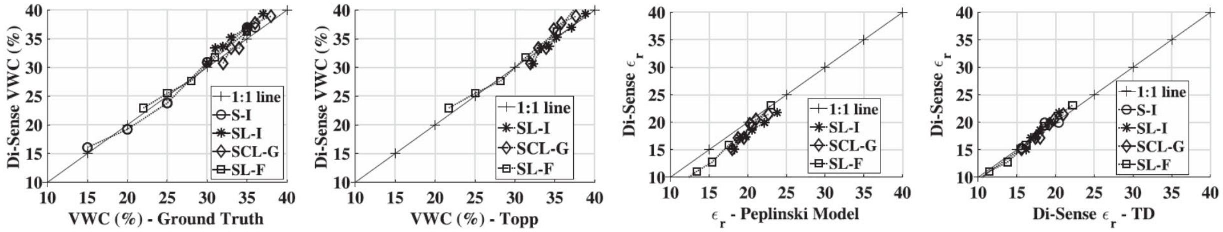
where l is the distance between transmitter and receiver antennas, $\tau_{dr} - \tau_{dt}$ is travel time of the direct component in the soil, and C_s is the wave propagation velocity in soil. Due to different propagation velocities of the air and soil, direct wave is separate from the lateral wave which travels through the air along the soil–air interface, and has less attenuation as compared to the lateral wave.

The relationship of the soil moisture and permittivity is independent of the soil texture, bulk density, and frequency. Since, soil permittivity depends on the soil moisture only, soil water con- tent can be determined from soil permittivity. 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:

$$VWC(\%) = ((\varepsilon_r - 3) / 0.77) + 14.97. \tag{7}$$

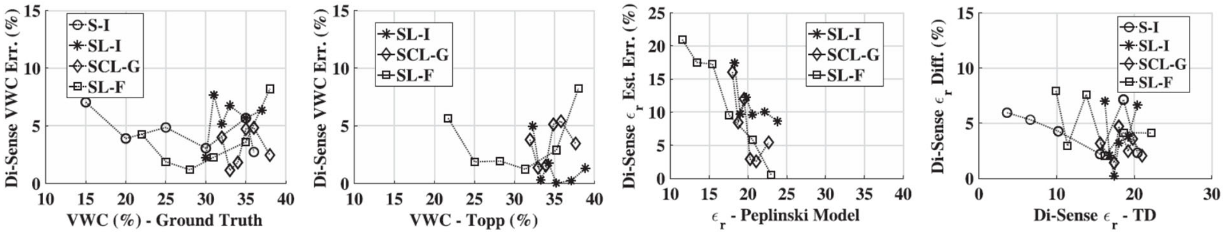
Experimental Setup

In this section, a brief description of the testbeds used in the analysis is provided. It is then followed by the techniques employed in UG channel measurements. A facility has been prepared in a greenhouse setting. Purpose of this facility, referred to as indoor testbed, is to conduct IOUT channel modeling experiments. In IOUT deployment of UG communication devices is limited to 50 cm depths. These burial depths are close



(a) (b) (c) (d)

Fig. 1. (a) Di-Sense VWC compared with ground truth VWC measurements (Salam et al., 2019), (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.



(a) (b) (c) (d)

Fig. 2. Di-Sense error analysis (Salam et al., 2019): (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.

to the surface of the earth, therefore waves propagating from UG devices travels along soil air interface. In the indoor testbed, four dipole antennas are buried at 10 cm, 20 cm, 30 cm, and 40 cm depths, and these antenna settings are extended to 50 cm, and 1m distances. Due to higher attenuation in soil, only distance up to 1m is considered. This structure helps in verifying the accuracy and repeatability of experiments such that role of receiver and transmitter antennas can be switched, and channel symmetry can be investigated. Moreover, multiple burial depths help to capture the depth effects on the channel. To compare the results of indoor testbed experiments, and to evaluate the effects of distance, a testbed of dipole antennas has been prepared in an outdoor field in silty clay loam soil. Dipole antennas are buried in soil at a burial depth of 20 cm with distances from the first antenna as 50 cm to 12 m. A testbed to conduct UG software-defined radio experiments has been developed in South Central Agricultural Laboratory (SCAL), University of Nebraska-Lincoln. Testbed in SCAL (South Central Agricultural Laboratory) consists of 4 sets of buried dipole antennas. Each set contains four dipole antennas buried at 50cm, 2m, and 4m distances.

Since variations in soil moisture affects the UG communications, hence, it is important to monitor and log the soil moisture with each experiment to accurately characterize channel behavior. In these measurements, Watermark sensors are used to log the soil moisture with time. It is also fast, efficient method and is less error-prone. Soil moisture logging can also overcome the disadvantages of oven drying method of soil water content determination where the soil has to be removed from the testbed for laboratory analysis. Further, it has been observed in that presence of a metallic object in the close vicinity of the buried antenna interferes with communication. Therefore, to avoid any interference, soil moisture sensors are installed at the edges of the testbed. Measurements are taken using Keysight Technologies N9923A FieldFox Vector Network Analyzer (VNA). Two types of measurements are conducted in the indoor testbed. VNA takes the transmission S21 measurements for an UG transmitter and receiver (T-R) pair by transmitting a known signal and then loss is measured at the receiver by comparing the received signal with the sent signal. Path loss is the ratio (expressed in decibel (dB)) of the transmitted power *Pt* to the power received *Pr* at the receiver. Path loss measurements for the UG channel are taken from 10MHz to 4 GHz frequency range in 401 discrete frequency point at different depths and distances.

Results and Conclusions

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 Eqs. (5) – (7), and results are shown in Fig. 1. In Fig. 1(a) and (b), Di-Sense VWC is compared with ground truth VWC measurements and Topp model. Di-

Sense permittivity is compared with Peplinski model in Fig. 1(c). 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. 1(d). While these graphs clearly show an excellent match of ground truth measurements and the models with Di-Sense, many interesting points are shown in Fig. 1. It can be observed that with decrease in lowest path loss frequency, soil permittivity increases rapidly, which also lead to increase in soil moisture. Results of model error analysis are shown in Fig. 2. In Fig. 2(a), 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. 2(b). 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. 2(c). 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, and soil bulk density) affect the soil permittivity. 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.

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