Employing a metamaterial inspired small antenna for sensing and transceiving data in an underground soil sensor equipped with a GUI for end-user

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Abstract—A methodology to extract sensor data from underground, in-situ, multi-frequency soil content sensors is presented. The underground sensor, that contains a small metamaterial inspired antenna that doubles up as a sensing element, measures the impedance of the surrounding soil by sending multiple signals of known frequencies in the range 1-40 MHz and comparing the magnitude and phase of reflected signal to those of incident signal. The amplitude and phase values that represent the reflection coefficient are stored in an internal register. In each transmission cycle, this packet is transmitted to an over ground receiver. The receiver decodes the data and processes it to extract the impedance value at the sensing element. The impedance values are then used to extract soil contents by solving certain dielectric mixing and relaxation models. A user-friendly graphical interface is developed that can support the automation of the whole process, and display the estimates of soil content as the output to help an end-user make effective decision about irrigation and fertilization.

Index Terms—Microstrip, GUI, Metamaterial, Composite-Right-Left-Handed transmission line, Spectroscopy.

I. INTRODUCTION

An underground soil moisture and salinity sensor needs to be efficient in terms of power consumption, user friendliness, accuracy, size, non-interference with agricultural activities on top surface and self-calibrating capability. In our earlier work [12], we presented a self-calibrating, multi-frequency dielectric sensor for combined moisture and soil ions sensing, while in [9] we showed how dielectric-mixing models can be reasoned to analyze the multi-frequency dielectric measurements to estimate the soil moisture and ion concentrations. Our work in [12], [9], [7], [10], [11] has shown that impedance spectroscopy based sensing has the potential to determine not only the amount of moisture in the soil but it also can detect and estimate the presence of ions in the soil. Advantages of measuring impedance of soil at multiple frequency include employing dielectric mixing models to estimate the moisture content apart from generating multiple data points at same frequency, thus improving data reliability [9], [8]. Such sensors have been shown to work in actual field setting with a common microstrip patch antenna used as the sensing electrode [10]. In another work [8], a small metamaterial inspired composite-right-left-handed antenna was shown to be able to detect the presence of moisture and salinity in soil. Moreover, the antenna provides more than 90% improvement in size over a similar microstrip antenna used in [10] at the transmission frequency of 433 MHz.

This work extends our previous work on metamaterial inspired small antenna [11] by providing estimates for soil moisture and salinity based on Bruggeman mixing model and also presents a graphical user interface to make the sensing process friendly to the end user. Main contributions of this work can be summarized as:

1) Employing the metamaterial inspired CRLH antenna that reduces the antenna size by more than 90% of the original patch antenna for estimating the soil moisture and salinity.

2) Introducing a sleep mode in the sensor hardware that can turn the sensor to low power mode when the measurements are not being made. In the sleep mode, the power consumption is only 450 µW as compared to 1.8W in full operational mode (or wake-up mode).

3) Developing a GUI that can help a naive user to collect impedance data, send the sensors to sleep (low-power) mode, view the current volume fractions of soil moisture and salinity present in soil.

Rest of the paper is organised as follows: Section II briefly discusses the existing state-of-the-art in soil sensing. Section III talks about the architecture of our sensor. Section IV summarizes our work on using small metamaterial inspired antenna as the sensing element. Section IV-B discusses the estimated of soil moisture and salinity that were calculated using this small antenna. A GUI for our sensor which can be used by the end-user is summarized in section V while section VII concludes the paper and provides an overview of current and future work being carried out by our group.

II. BACKGROUND

Multi-frequency measurements on a soil sample have been shown to help in detecting the nitrate and chloride concentration in soil [1]. Main approach for making multi frequency
measurement has been well known time domain spectrometry (TDR). In this method a square signal pulse of known properties is reflected from an unknown surface and time difference between transmitted and received waves is used to determine the surface impedance. TDR approach has been extended to determine nitrate and chloride concentration in soil as well. In [6], authors present an in-laboratory method to detect nitrate concentration using TDR approach. A potassium nitrate solution of known concentration of 500ppm was flown through the TDR sensor contained in soil inside a plexiglass cell. Nitrate concentration was changed with time and the TDR probes were placed at regular intervals along the flow cell. The bulk soil electrical conductivity and the water content values extracted from the TDR wave forms were used to predict the nitrate concentrations at different locations. The nitrate concentration values predicted from the TDR-measured bulk electrical conductivity and water content data were observed to correlate with the nitrate concentrations obtained by soil solution sampling method. In [1] the variation of soil permittivity and soil conductivity with frequency from 200 Hz to 13 MHz has been presented. It has been shown that TDR approach can be used to effectively detect nitrate concentration by measuring the soil permittivity and conductivity.

Our approach involves reflection as in TDR systems, but instead of measuring the time delay or phase shift we measure the impedance of the soil under observation. This is beneficial for real time sensing as the surface under observation can be outside of the system unlike [14] which needs waves to travel through the conductor contained in the line. Our previously built system ([12]) has the capability to make measurements at multiple frequencies and is self-calibrating which makes it more robust, more accurate and low maintenance. The use of transmission line model allows us to include line losses and calibrate the system periodically. Due to multi-frequency approach, our sensor has the capability to detect and transmit information about soil moisture as well as ionic concentration [1]. Using de-embedding techniques, some of the disadvantages related to TDR sensors like inaccurate measurements due to probe length have been minimized.

III. PRIOR WORK: ON-BOARD MULTI-FREQUENCY IMPEDANCE SENSOR

We have recently designed and tested a dielectric measurement based soil impedance sensor that can sense at multi-frequencies (hence accurate & reliable), is self-calibrating (hence robust), possesses wireless interface (hence can be located in-situ), and is also energy-efficient [12]. The sensor architecture, consisting of probe and antenna, directional couplers, phase locked loop (PLL), amplitude and phase detector, switches/diplexer, microprocessor & transceiver, is shown in Fig. 1.

Upon startup, the microprocessor programs the I2C interface of the programmable PLL to generate a signal of known frequency. The frequency of the probing signal is chosen in the range of 1-40 MHz, and is chosen so that a significant variation in real and imaginary part of the soil impedance can be observed. While the lower limit of 1 MHz on frequency is put by the architecture of the sensor, the upper limit of 40 MHz was obtained experimentally as above this value the soil reactance becomes close to zero. A slight increase in this value can provide more data points to analyze but beyond that no useful information on soil ionic concentration can be extracted from it. The probing signal is sent through the transmission line to the SP6T switch, which is programmed by the microprocessor to select among a set of known loads plus the unknown soil-sample load. The incident and reflected signals to and from the load are captured using the directional couplers and are passed on to a detector which calculates the amplitude and phase of each signal and passes this information to the microprocessor for further processing and transmission via antenna. These values are received by the microprocessor through an in-built 12-bit ADC. In the calibration mode, when the loads are of known values, these values are used to calculate the calibration parameters that correlate the reflection coefficients (ratio of reflected to incident) measured at the couplers to those at the load through a 3-parameter bilinear transform. In the measurement mode, when the load is the soil-sample, these calibration parameters are used to find out the reflection coefficient for an unknown load from its value measured at the directional coupler, through the same bilinear transform whose parameters were determined in the calibration mode. The reflection coefficient value is then used to determine the unknown load impedance that contains the information about the soil contents (moisture and nutrients).

The resistive versus reactive soil impedance measurements over 1-40 MHz by our sensor are shown in Figs. 2 and 3. The accuracy of our in-situ sensor is confirmed against the measurements from a lab equipment, a network analyzer, HP8714ES (plots also shown in the same figures). A more than 90% accuracy over the range of 1-40 MHz in soil reactance was observed.

IV. METAMATERIAL INSPIRED SMALL ANTENNA

Metamaterials are specially constructed designs which offer electric and magnetic properties opposite of materials found in nature such as negative permittivity and permeability. This creates a possibility of engineering a small-sized metamaterials
matching network between the antenna and the surrounding medium so that the energy stored in the near field is radiated away. Size improvements of factor greater than 10 compared to standard antennas have been observed in [2], [16], [15]. Authors in [2] discuss a composite right-left handed (CRLH) transmission line based antenna, with potentially improved efficiency for small patch antennas. Another such implementation has been reported in [3]. In this paper, we present another design based on a standard CRLH structure [2] that can also be used as an underground sensing element (see Fig. 10 and its fabrication in Fig. 9).

A. Admittance variation with varying moisture and nitrate conditions

Figs. 4 and 5 show the variation in admittance with changing values of sodium nitrate solution. A 100 mili molar sodium nitrate solution was added in steps of 4% by volume increments to the soil that had sensor with the patch, acting as a probe (as well as antenna, at another frequency), buried into it. It was observed that the measured conductance (reciprocal of the real-part of impedance) of the patch increased as the concentration of sodium nitrate was increased in soil, whereas there was a much smaller variation in the susceptance (reciprocal of the imaginary-part of impedance) value. This demonstrates that the accurate measurement of soil impedance (equivalently, admittance) using microstrip patch sensing probe at multiple frequencies has the potential to successfully detect changes in ionic concentration in soil. The dielectric mixing models [13] that determine the permittivity of a mixture as a function of the composition and content of the mixture, together with the dielectric relaxation models [4] that determine the permittivity as a function of the frequency can be employed to estimate the concentrations of moisture versus nitrates versus air in the soil from the measurements, as is the case in [7].

B. Estimation of water and nitrate using CRLH sensing element

Using Bruggeman mixing models, [9], the estimated fraction of solution is shown in Fig. 6 and compared with the actual amount of solution added. High inaccuracy is observed for high concentrations (more than 20%). In the low-range (less than 8%) the maximum error was found to be less than 20%. One factor that causes larger error for lower concentrations is the initial amount of solution acts as bound [4] and hence needs to be treated separately. On assuming a 4% fraction of bound solution, the results are within 10% of the actual value.
of the saline water fraction.

The conductivity of a dielectric mixture has been shown to increase with increasing concentration of saline solution. The conductance of soil dielectric mixture is proportional to the imaginary part of dielectric permittivity. For a dielectric mixture with saline solution as a constituent, all the conductivity is provided by the moving ions in the saline solution. The other constituents, air and soil bulk are non conducting. Hence, once we have an estimate of fractional volume of saline solution, we can predict the amount of ions present by relating the conductivity at a single frequency with the molar concentration of ions present in the overall volume. The increase in conductivity at 1 MHz with increasing molar fraction on sodium nitrate is shown in Fig. 7. At concentrations above 20 \( \mu \text{M} \), the conductivity is linear. Since a 50 mM solution of sodium nitrate was used for the experiment, the lower concentration of nitrate implies a lower concentration of fractional saline water volume which in turn means a larger fraction of saline water being in the bound form. Since conductance is directly proportional to the concentration of ions in water, a linear relation between conductance and concentration is expected. The measured value of average conductance for complete frequency range is quite close (within 5% of margin) to the expected linear model. Slight deviation is observed as soil is not a homogeneous solution and saline water is not uniformly distributed.

V. GUI FOR INTERFACING WITH THE SENSOR

A GUI is a graphical interface that allows user to interact with the electronic devices with ease using graphical icons without having prior knowledge of the underlying mechanism. Its primary purpose is to make the task simple to the user by performing some actions in the backend and displaying the result in the frontend visually/ graphically. In this paper, we have developed a Soil Sensor GUI that allows a user to input a set of impedance data collected from the electrode embedded in soil under observation and display its result by plotting the graph on the axis in the frontend. Some of the key controls/displays in the GUI are as follows:

1) Sensor state: It is used to control the state of the sensor—sleep or wake up state. In the sleep state, no data is transmitted by the sensor. The sensor is in receiving mode and is waiting for an external trigger to wake it up in order to make impedance measurements. In this mode, sensor consumes approximately 450 \( \mu \text{W} \) of power. In the wake up state, the sensor is in active mode and impedance data is transmitted to the receiver. Once a measurement is made, sensor goes back to sleep mode until next trigger arrives. In the wake up mode,
Sensor consumes approximately 1.8 W of power. A single measurement over 10 different frequencies last for 1.5 minutes.

2) Mode: In the wake-up state, user can choose to calibrate the sensor or decide upon making the measurements without any calibration. Calibration itself can be hardware calibration \cite{12} or impedance to moisture and salinity model calibration \cite{9}.

3) Model Type: Once sensor has made the measurement of soil impedance at multiple frequencies, it can infer soil moisture and salinity values either based on a physics based model as in \cite{9} or an empirical model as in \cite{1}. Further work is being done on refining these models according to a specific soil type and weather information.

4) Impedance: The impedance display of electrode buried in soil provides an estimate of moisture and ions present in the soil at the time of measurement. This impedance value is dynamically displayed in the GUI. The user can also input a frequency and get the corresponding impedance reading. The measurement value at a single frequency can be displayed by entering the particular value in the textbox before clicking RUN button.

5) History: This display allows user to view old moisture and salinity data for any past range of maximum 10 years. This can help predict the current and future moisture and fertilizer requirements for the user.

There are four input buttons, RUN, RESET, SUBMIT and Log File. The RUN button generates the graphical output to the user. When this button is clicked, it will invoke a callback function and perform action based on the input collected from the user and display the output to the user. The RESET button is used to clear all the input entered by the user. SUBMIT button submits the range of date user wants to choose in order to view past moisture and salinity data. Log File button will pull out all the past values for the range of dates submitted in a text file.

VI. Power Consumption and Packaging

A. Improving power consumption by using sleep mode

Due to the presence of a power amplifier in the transmission path, the sensor consumes high power while transmitting the measurements (the wake-up mode). Inside this mode, there are two sub-modes of power consumptions. When the sensor is not transmitting and only the impedance spectroscopy is taking place, the total current consumption from a 9V battery is 170 mA. When the transmission of data takes place and the power amplifier is operational, the current consumption goes up to 300 mA. Since, transmission contributes to a very small fraction of overall operational time, the average current consumption for complete operational cycle is 200 mA, which implies for a 9V battery 1.8 W of average power in operational mode. Once the data is transmitted and no further wake-up signal is received, the sensor goes into sleep mode. In this mode, only the microprocessor is active and is listening to any pings from the remote transmitter. The power consumption in this mode is 450 $\mu$W. Since sensor is operational for only 1 or 2 measurements a day, it mostly remains in sleep mode. In this mode, the average power consumption based on daily usage is 1.7mW, which means that a 5000 mA-h/9V battery will last for around 1100 days (nearly 3 years) of continuous underground operation.
B. Packaging

All the individual components of sensor are packaged inside a waterproof acrylic box of dimensions $3'' \times 2'' \times 0.8''$ (See figure 11). Antenna is placed in a patch-like slot on the topso it can be in direct contact with the surrounding soil. Sensor electronics is protected from external environment and is placed inside the box. Antenna is connected to the circuit by a coaxial cable. Batteries are placed below the sensor.

VII. CONCLUSION AND FURTHER WORK

A small metamaterial inspired antenna was shown to be an effective sensing electrode for soil moisture and salinity sensing. It was shown that the impedance data collected from the sensing element can be transmitted to a remote receiver using the same antenna with transmission occurring at a frequency of 433 MHz. The data received remotely can be analyzed to estimate the fraction of soil moisture and salinity. A graphical user interface has been developed which can be used by a user to operate the sensor remotely. To improve the power consumption efficiency, a sleep mode is introduced in the hardware. Very little power consumption in this mode allows the sensor to last underground for a longer duration with average power consumption of sensor being only 1.7 mW. Efforts are underway in our lab to further improve the power consumption efficiency of our sensors by deploying small underground vibrational energy harvesters [5] that can partly provide additional back up for the power requirements of our sensors. Further efforts are being pursued to separate out the ions in the soil in order to detect each ion (e.g. nitrate/phosphate/sulphate) individually so that a highly accurate fertilizer level monitoring can be done. Another plan is to extend these sensors to multi layered structures so that moisture and salinity concentrations at multiple depths at a single location can be made.

REFERENCES