Agricultural Cyber-Physical System: In-Situ Soil Moisture and Salinity Estimation by Dielectric Mixing

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ABSTRACT Integration of cyber technologies with agriculture provides opportunities for precision agriculture. It requires buried underground sensors to provide useful content information to the end-user for crop management. In our earlier studies, we developed an impedance measurement-based in-situ wireless soil moisture and salinity sensor, an electrophoretic sensor for measuring soil ions/nutrients, and nano-patterned plasmonic-resonance, as well as guided-mode resonance-based optical sensors for the plant, released volatile organic compounds. Here we present a physics-based approach to infer the moisture and ionic concentration in the soil from in-situ, multi-frequency measurements of the impedance of a metamaterial-inspired sensing element buried underground. Such model holds the advantage over empirical models by obviating the need to redo the calibration for different soil types. Our method involves performing an inversion analysis on the Bruggeman's dielectric mixing model. Under the quasi-static assumption, the approach predicts volumetric moisture content and ion concentration with 90% accuracy in terms of the molar fraction of total volume for silver nitrate concentrations of 0 to 100 mM. We observed that soil conductivity is near-linear to the inferred ionic concentration for a given saline water fraction in the soil. The model has been validated by making multi-frequency impedance measurements of a soil mixture at different concentrations comprising of various constituents of soil, air, water, and ions.

INDEX TERMS Agriculture, fertilizer, irrigation, sensor systems, soil moisture, soil properties, wireless sensor.

I. INTRODUCTION

Cyber-physical systems integrate cyber elements to physical components to obtain precise control and optimization. An application is precision agriculture, where managing the nitrogen cycle has been identified as one of the fourteen grand challenge problems by the National Academy of Engineering. In this context, in our earlier studies we developed an impedance measurement based in-situ wireless soil moisture and salinity sensor [1], an electrophoretic sensor for measuring soil ions/nutrients [2], and Nano-patterned plasmonic-resonance as well as guided-mode resonance based optical sensors for plant released volatile organic compounds [3]. We also developed an efficient networking of such sensors [4], and used the network for sensor-node localization based on received signal strength [5] and time-of-arrival information [6]. Further, we developed a broadband vibrational energy harvesting mechanism for powering remote sensors, using a bi-stable piezoelectric cantilever design [7]. Due to variable soil nutrient availability across the field, the current practice of yield-driven uniform application of agriculture resources leads to tremendous losses and also impacts the environment. In case of agriculture, the intra- and inter-field variabilities are characterized using a network of sensor nodes spread over a large area (see Fig 1). Each node in such a network conveys the localized information that can be used to develop a deeper understanding of agricultural process so that precise controls over inputs that are the key to sustainable agriculture can be implemented. Each sensor node sends this local information about the properties of the soil in its vicinity to a central node, which processes the information and takes necessary control measures towards irrigation, fertilization, and other applications. The in-situ, buried impedance spectroscopy based sensing has the potential to determine not only the amount of moisture in the
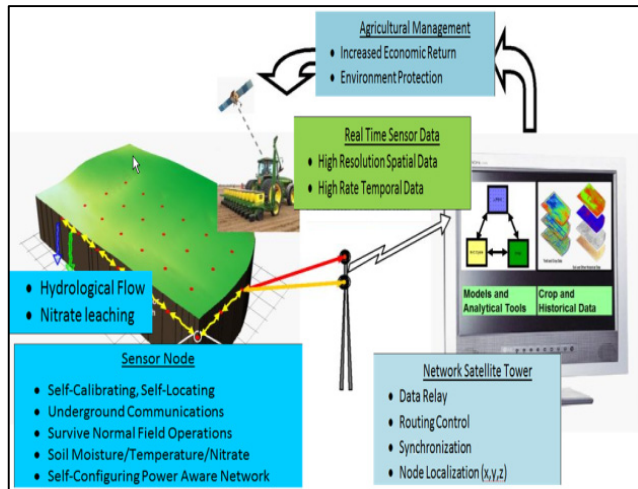
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FIGURE 1. A Generic Precision Agriculture model.

soil but it also can detect the presence of ions and their concentration in the soil. Using impedance spectroscopy for measuring impedance of soil at multiple frequencies allows for inverse analysis of dielectric mixing models to estimate the moisture and ion concentrations, apart from generating multiple data points at the same frequency, thus improving data reliability.

Impedance spectroscopy based sensors have been shown to work in actual field setting with a common micro-strip patch antenna used as the sensing electrode [8]. A thorough review of various existing sensor technologies is provided in [9]. This work also details data analysis methods for upscaling from a point to give an aerial average over a large number of sensors. Electrical property based sensors are evaluated in [10] where changes in electrical properties of soil were evaluated in 1Hz-40MHz range. This study establishes that point electrodes are suitable for establishing moisture and contaminant profile in soil in a lab setting. In another study [11], the effect of frequency on complex permittivity is detailed in the 0-1GHz range. In-situ imaging using GPS radar is performed in [12] and time-domain reflectometry (TDR) for the in situ assessment of high-frequency electrical properties and deduced prediction of GPR performance.

A challenge still remains to extend the functionality of established sensor and modelling techniques to estimate moisture as well as ions in soil. Moisture and ions distribution using TDR are studied in [13]. In this study, the relationship between conductivity and volumetric water content is studied. It was shown that conductivity estimated using TDR can be used for continuous monitoring of soil nitrates in Andisol fields. Once sensing is performed, next step is to estimate the constituents in soil. A review of measuring soil water content by the way of conductivity measurements is provided in [14]. An empirical model relating bulk soil electrical conductivity, volumetric content, and electrical conductivity of soil water is given in [15] along with supporting evidence for its validity. In [16], a capacitance probe frequency response model

accounting for bulk electrical conductivity has been evaluated in comparison with TDR. In [17], impacts of the real and imaginary components of relative permittivity on TDR measurements in soils is examined and it is shown that real part of permittivity is determined primarily by water content in the soil. An inversion analysis based method to estimate soil constituents has been presented in [18] for estimating soil water and air fractions using dielectric mixing models combined with spectrum analysis. In [19], time domain reflectometry is utilized to measure volumetric water content and organic compounds using a dielectric mixing model. It is established that dielectric mixture model can be used to identify the soil contamination. In [20], inversion analysis of two mixture models is performed to predict the capacitance measurement data for different soil saturation levels using a electromagnetics (finite-element) based model.

A method to determine the equivalent permittivity of a mixture like soil is by using the dielectric mixture models [21]. Dielectric mixing models are used to determine the permittivity of a mixture in terms of the permittivity and concentration of its constituents. Many dielectric mixing models such as Maxwell-Garnett, Bruggeman [21] and deLoor's mixing rule [22] have been shown to be useful in describing soil moisture content given that the permittivity of other constituents like bulk soil, trapped air and bound and bulk water are known, where bound water can be assumed to have the electrical properties of ice. This assumption has been validated by making accurate measurements of soil moisture using the dielectric measurements [23].

In order to use dielectric mixture models to determine individual constituent fraction, we need to measure overall permittivity of the dielectric mixture at different frequencies. Since permittivity itself is not a directly measurable quantity, in order to determine the permittivity of a mixture, a directly measurable electrical property such as impedance needs to be measured. In this paper, we use the dielectric mixture models to determine the concentration of moisture and ionic constituents in the mixture of bulk-soil, air, water, and ions. This is accomplished by first measuring the overall permittivity of the soil mixture at multiple frequencies, and then using a dielectric mixture model to form equations in the constituents of the mixture.

We use the input impedance of a metamaterial-inspired patch embedded in soil sample as a measurable property, which is known to be linearly related to the permittivity, and propose a method to determine the concentration of ions in a mixture like soil using impedance spectroscopy. The need for multiple frequency measurements arises because from a single frequency measurement, concentration of more than one unknown constituent cannot be determined, regardless of the accuracy of the measurements. Since all parameters, including permittivity, of each constituent are known except their concentrations, for a host with n-constituent, measurements at n frequencies can give adequate information to infer the n unknown concentrations. If there are more than n measurements, then least square methods are used to find the

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"best" fitting set of unknown concentrations that minimize the squared-error of the fit.

A brief overview of the architecture of our sensor is also presented, that uses a small metamaterial-inspired patch that acts as sensing element for low frequencies (below 40 MHz), and duals as an antenna for communication at frequency of 433 MHz. The contributions of our work are as summarized below:

• Propose a method to determine the concentration of moisture as well as nitrate using multi-frequency impedance measurements and solving mixing plus relaxation models. (Measurement frequency range is determined by actual in-situ sensor previously developed by our group);

• It is shown that above method can be used in conjunction with a metamaterial-inspired patch that can double up as an antenna [24] thus providing a way for small in-situ wireless underground sensors;

• Validation of the proposed method on a soil sample collected from the field.

Following sections in the paper are organized as follows: Section II reviews the existing state-of-the-art in soil moisture and nitrate detection, modeling, and estimation; section III discusses a previously built in-situ on-board sensor that can perform underground multi-frequency measurements and transmit the data out to a base station section IV discusses the proposed approach that has been employed to determine the moisture and ionic concentrations. Section V explains the experimental setup that was used to validate the theory; Section VI presents the observations and trends in impedances variations; Section VII analyzes the result; Section VIII concludes the paper with discussions for future directions.

II. BACKGROUND WORK

Architectural implementation of the physical layer of a soil content sensor determines what measurements a local node in will perform. For each sensing node an accurate, real-time, and in-situ soil content measurement is needed while maintaining robustness and low-cost. Such measurements over a wide area provide information about the required content that need to be added such as moisture or fertilizers. From a local node perspective, an efficient soil content determination approach involves:

• Estimation of soil moisture content that is present along with soil bulk and air molecules,

• Determination of soil ionic concentration based on change in soil properties.

These can themselves be broken down into two problems:

• Developing an efficient model to map a known amount of moisture and ionic level in a given soil to the property being measured such as permittivity of the soil mixture;

• Once a good model is developed, soil mixture permittivity with unknown moisture and ionic content is measured, which is then be mapped to the amount of moisture and ionic content present using the model developed

Finally, for an in-situ real-time approach one would want to wirelessly transmit the information from buried sensors in the field to an over ground central station that can process and supply information to the end-user. This section reviews the existing literature taking account of each of the points mentioned above.

A. SENSORS FOR AGRICULTURAL CYBER PHYSICAL SYSTEMS

With ever increasing demands on agricultural production, it has become imperative for information and communication technologies to play a bigger role in not only increasing the agricultural production but also ensuring that effect on environment is minimal [25]. Sustainable agricultural practices call for methodologies that utilize existing and proven principles from paradigms such as Cyber Physical systems and Internet of things. Such system consists of physical layer of sensing node buried in the field such as in [24] and [26]. Other aspects of such work [4], [5] include data-link-layer of a wide network of such sensors. The network of sensors is expected to achieve maximum data throughput while consuming minimum energy. [4], [27] provide a solution by providing a design of a network that periodically collects data from fixed locations in the field. Each node has the ability to operate in multiple power nodes for purpose of achieving energy savings. Moreover, unique sleep and wake-up states at each node allows the MAC protocol to be more energy efficient. Sensor node localization is another problem sensor networks have to deal with. Node localization is imperative to make sure the end-user understands the position of sensor in the field and responds accordingly to the sensed data such as addition of moisture or fertilizers at the location. This has been addressed in [5] and [6]. Time of arrival criteria has been utilized in [6], while received signal strength is used for node localization in [5].

Apart from design of physical and data-link layer for sensors, a sustainable soil sensing network needs continuous inflow of electricity to keep the nodes powered up. One way to achieve a long term power solution is through vibrational energy harvesting techniques. In [7] and [28] Singh *et al.* present a bi-stable broadband cantilever based piezoelectric energy harvester that can transduce ambient vibration energy, with synchronized capture for efficient harvesting over broadband vibrations. Owing to combined bi-stability and synchronized harvesting, significant increase over existing power generation techniques was reported in authors' work.

Other than the electronic sensors as reported in this paper, electrochemical sensors for ion specific detection have also been presented in literature. In [29], a method to track water transport inside the plant by using multiple graphene oxide based relative humidity sensors is presented. The sensor is developed on an adhesive polyimide film by selectively coating a Graphene oxide layer on top of gold interdigitated electrodes and subsequently peeling the whole device structure off from a pre-coated polydimethylsiloxane temporary layer. In another such work [3], Ali *et al.* present

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a microfluidic nitrate sensor using a graphene foam based electrode modified by titanium dioxide nanofibers and nitrate reductase enzyme molecules. This sensor is highly sensitive to nitrate ions and shows fast detection time. In [2] and [30], an electrophoresis based microfluidic approach to ion nutrient sensor for detection of anions in soil solution samples is presented. Such device can detect multiple ions present in a solution in a rapid and sensitive way. The sensor works by way of high voltage electrophoresis that results in peak as ions reach the electrodes. Difference in mobility of ions results in peaks separated in time and detection of such peaks helps in detecting and separating ions in the solution.

B. SOIL MOISTURE CONTENT DETERMINATION

Soil moisture content determination has been a widely studied topic and many different approaches have been studied in the past to achieve accurate soil moisture estimation. In [14], Time Domain reflectometry (TDR) based approach has been discussed in detail. In the TDR approach, dielectric constant is measured by measuring the propagation time of electromagnetic waves sent through a pulse generator. The time difference between [31] incident and reflected signal is dependent on the permittivity of the material from which signal is getting reflected from. Moist soil shows propagation time that lies in between dry soil and distilled water and by measuring this time, an estimate of the dielectric constant of the moist soil mixture can be made. To estimate the soil moisture content, an empirical formula provided in [17] is used:

$$\theta = -5.3 * 10^{-2} + 2.92 * 10^{-2}\kappa \\ - 5.5 * 10^{-5}\kappa^2 + 4.3 * 10^{-6}\kappa^3, \quad (1)$$

where θ is volumetric water content while κ is the dielectric constant measured using the TDR approach.

Other models to determine soil moisture content using changes in dielectric constant have also been proposed. In [32], another such equation is introduced. This equation [33] incorporated the effect of soil bulk density (ρ_b) apart from dielectric constant in (1):

$$\theta = \frac{(\kappa^{0.5} - 0.819 - 0.168\rho_b - 0.159\rho_b^2)}{(7.17 + 1.18\rho_b)} \quad (2)$$

In the TDR based approached to soil content determination, one uses a network analyzer that connects with an electrode probe that is immersed in the soil under consideration to determine soil moisture content [16]. In this approach, capacitance of a probe immersed in soil is measured and change in capacitance is correlated with the moisture content of the soil. The capacitance of an electrode immersed in soil is proportional to the dielectric constant:

$$C_{in} = \epsilon G_m \quad (3)$$

It is shown that the capacitance/dielectric constant measured using this technique can be used in the same way as measured using TDR technique. Once we get the dielectric

constants under wet and dry conditions, we can estimate the moisture content using the models described in (1) and (2).

Measurement of electrical conductivity is another method that has been used to provide insights into the soil content [9]. One model proposed in [34] is:

$$\sigma_a = \sigma_w \theta_{sat}^{1.5} \left(\frac{\theta}{\theta_{sat}} \right)^{2.5}, \quad (4)$$

where θ_{sat} is saturated water content and σ_a and σ_w are mixture and water conductivity respectively. The dis- advantage of this method over TDR or capacitance probe method is that the conductivity measurement in the soil can vary with amount of ions present and hence ion contribution need to be carefully held constant for saturated and in-situ measurements which is difficult to do in a real field.

Other approaches such as heat pulse sensors [35] that involve introducing a short heat pulse on one probe and measuring temperature on other are also explored. Such sensors in principle are deployable as in-situ but may require more power than TDR or capacitance based approach since heat dissipated has to come from remote power sources such as batteries. Another approach taken in literature is neutron probe based soil moisture sensors [36]. It depends on variation in the amount of secondary neutrons with change in soil moisture that are generated when high energy particles from outer space hit the soil. Such approach is suitable for large scale sensing such as in rain forests and may not prove to be as cheap as an electrical measurement based approach.

C. ELECTRICAL CONDUCTIVITY MEASUREMENT

Both TDR and capacitance measurement approaches can be extended to measure electrical conductivity which can provide insights into ion concentration in the soil. Electrical conductivity measurement using TDR has been discussed in [37] and [38]. In [37], electrical conductivity is expressed as:

$$\sigma = \frac{\epsilon_0 c}{L} \frac{Z_0}{Z_c} \left(\frac{2V_0}{V_f} - 1 \right), \quad (5)$$

where ϵ_0 is the dielectric permittivity of free space, c is the speed of light in vacuum, L is probe length, Z_0 is the characteristic probe impedance, Z_c is the TDR cable tester output impedance (typically 50 Ohms), V_0 is the incident pulse voltage and V_f is the return pulse voltage after multiple reflections have died out. The key principle here is to measure real part of impedance at low frequency which is why it is important to make this measurement after reflections from the TDR pulse have died down. In [38], further refinement to this approach is made by including a relaxation term in the overall conductivity:

$$\sigma = \frac{\sqrt{\epsilon_r'}}{120\pi L} ln \left(\frac{V_1(2V_0 - V_1)}{V_0(V_2 - V_1)} \right), \quad (6)$$

where V_0 is the incident pulse voltage, and V_1, V_2 are the return pulse voltage after first and second reflections. In a frequency based approach [39], a model for measuring conductivity and permittivity in frequency range 1 MHz to 1 GHz

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is developed. Frequency dependence of conductivity is related to permittivity as:

$$\epsilon = \epsilon' - j\epsilon'' = \epsilon' - j\frac{\sigma}{\omega}. \qquad (7)$$

A simplified linear model relating conductivity to the saline content is developed:

$$\sigma = \theta^m \sigma_w + \theta^{m-1} \sigma_s, \qquad (8)$$

where m is called cementation exponent and σ_w and σ_s are water and salt conductivity respectively. Another TDR based soil temperature and conductivity measurement is done in [33]. In this work, real-time monitoring of soil conductivity is done using a TDR system described by [37]. A TDR measurement system with inbuilt GPRS modem, Analog-to-digital converter and micro controller is used to generate and process information in real time. Such systems have the capability to evolve into in-situ underground systems by miniaturizing the system and adding a wireless transmission circuitry.

D. MICROWAVE BEHAVIOR OF SOIL MIXTURE AND THEIR MODEL

Under low salt concentrations, soil can be viewed as a mixture of 3 main constituent soil bulk, air, and water. Water exists in 2 main states in soil—bound vs. free water [22], bound water being the molecules of water that are close to the soil particles and hence are not as free to move as rest of the water in the bulk. It is shown in [22] that soil can be treated as a mixture of 4 components, and a 4-component mixing model determines the equivalent permittivity of the soil mixture. The permittivity of bound water is assumed to be between that of ice which is completely immobile and water which is completely mobile and is empirically determined. In [40], dielectric constant of wet soil is observed at microwave frequency range. It is shown that there is a slow increase in dielectric constant at lower per cent of water content whereas it increases sharply at higher water content and becomes constant at certain value of water content in soil. This is due to the fact that initial water added to the soil attaches to the surface of soil particles while once water is free to move, high dielectric constant of water causes effective dielectric constant to rise sharply. It is also observed that the value of dielectric constant decreases due to ionic effect.

Dielectric mixture models provide insights into effective dielectric constant of a mixture when a number of constituents with known permittivity are involved. Apart from using empirical models as provided in equations (2)-(6), we can also employ a physic-based approach to infer content from TDR or capacitance probe permittivity measurement. One such inversion analysis of dielectric mixture models is presented in [41]. In [41], a semi-analytical approach to obtain an equivalent Debye frequency dependence of effective permittivity for two phase materials with unknown spherical inclusions from the Maxwell Garnett mixing rule is proposed.

According to the Maxwell-Garnett rule, the permittivity of the mixture ϵ_{eff} satisfies:

$$\frac{\epsilon_{eff} - \epsilon_{host}}{\epsilon_{eff} + 2\epsilon_{host}} = f_i \frac{\epsilon_i - \epsilon_{host}}{\epsilon_i + 2\epsilon_{host}}_i \qquad (9)$$

For multiple inclusions, this formula extends to:

$$\frac{\epsilon_{eff} - \epsilon_{host}}{\epsilon_{eff} + 2\epsilon_{host}} = \sum_i f_i \frac{\epsilon_i - \epsilon_{host}}{\epsilon_i + 2\epsilon_{host}} \qquad (10)$$

The Maxwell-Garnett rule is quasi-static in nature, which means it is valid, when the size of inclusions is much less than the wavelength in the medium. The Maxwell-Garnett model is applicable to a mixture containing conducting inclusions in a dielectric host as long as the volumetric concentrations of conducting inclusions remain below the percolation threshold [42]. According to [42], if inclusions are conducting in nature, their volume fraction should be less than the percolation threshold. Theoretically, spherical inclusions may start touching each other in a 3-dimensional periodic lattice at the volume fraction above 47%. Practically, in a random mixture, the limit is no more than 20%–30%, since inclusions may interact and build conductive chains.

High frequency behavior of a dielectric material is expressed using Debye relaxation rule which is given by the equation:

$$\epsilon = \epsilon_\infty + \frac{\epsilon_S - \epsilon_\infty}{1 + j\omega\tau}, \qquad (11)$$

where ϵ_S the permittivity of the molecule at very low frequencies, ϵ_∞ is the permittivity at very high frequencies, τ is the relaxation time, which is defined as the time required by the molecular dipole to reach a new equilibrium when a time varying external electric field of a certain frequency is applied. In [41], 6 different mixture cases are considered, each being different cases of 2 constituents of the mixture being either Debye, conductive, or constant dielectric constant. It is shown that theoretical Maxwell-Garnett rule and Maxwell-Garnett rule with Debye relaxation included behave the same way for concentrations of inclusions below 20% even for frequency higher than few 100 MHz. This shows that the Maxwell-Garnett and related mixing models have the potential to be inverted to estimate the constituents if dielectric constant of the mixture is measured. One such inversion approach is taken in [18].

In the present work, it is shown that an inverse mixing model can be efficiently used for a four phased system of soil, air, bound, and free water. It is shown that although, predicted relaxation frequency using generic mixing rule is higher than measured relaxation frequency, the relaxation itself happens in GHz frequency range and model needs to account for Debye relaxation if frequencies of the order of few GHz range are being used for measurement. In [43], a model for effective permittivity of a mixture as a function of frequency based on equivalent circuit approach is presented. It is shown that beyond relaxation frequency of few 100 MHz, the equivalent capacitance of overall mixture goes down. For

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low frequencies, however, the effective capacitance is the sum total of individual capacitance (of constituents). Above examples show that inverting a dielectric mixing model is a useful approximation especially if frequencies in low MHz range are utilized.

E. NITRATE DETECTION IN SOIL

Nitrate is one of the most important ions that affect not only the crop yield but also the environmental conditions around the field, underground water table, as well as aquatic ecosystems surrounding the region [44]. Geostatistical techniques have been developed in the past to assess spatial and temporal variation in NO3-N concentrations in soil apart from moisture and spatial structure [45]. However, since such methods are based on statistical analysis on laboratory data, there exists a need for in-field measurement of actual spatial and temporal variation in NO3-N distribution, when using these measurements for implementing precision agriculture practices. One such in-field work has been detailed in [46]. In this work, a prototype ion-selective filter based soil sampling wheel, indexing and processing table and data acquisition tools and control is developed. In another microfluidic based sensor [47], graphene oxide Nano-sheets are used to electrochemically sense the nitrate ions present in the soil. An array of such nodes combined with wireless transmission to soil above ground can provide valuable data about soil nitrate to the end user.

F. WIRELESS TRANSMISSION USING UNDERGROUND BURIED ANTENNA

Once a sensor based on above discussed principals is built to make the measurements, a next task is to build a transmitting system that has the capability to transmit the signals through the lossy medium of soil to a sufficient distance above the ground. Another approach can be to perform the sensing using ground penetrating radar (GPR) such as in [48]. Such approach suffers the drawback of having low resolution but is advantageous in characterizing a large area from a remote location such as satellite station. In [48], a time propagation model based approach is used. The mathematical model describing such model is:

$$\epsilon_r = \left[\sum V_i \left(\epsilon_i^\alpha \right) \right]^{\frac{1}{\alpha}},$$ (12)

where α is a geometric constant that relates the direction of the effective layering of components to the direction of the applied electrical field. This model does not account for variations in frequency; therefore, modeled bulk dielectric-constant values are valid only at the specific frequency for which the input component dielectric constants are representative. A wireless multi sensor platform is discussed in [49]. This sensing system has the capability to transmit signal using a ZigBee platform and make impedance measurements on soil using on-board network analyzer in the frequency range 5 KHz to 100 KHz. Another in-situ GPR based approach is taken in [12]. To derive the complex dielectric

permittivity in 1 MHz to 10 GHz range, a coaxial transmission line based approach to permittivity measurement is used, along with the Cole-Cole relaxation model:

$$\epsilon_\omega^* = \epsilon_\infty + \frac{\epsilon_S - \epsilon_\infty}{(1 + j\omega\tau)^{1-\alpha}}$$ (13)

which becomes same as Debye model for exponent parameter $\alpha = 0$.

In our group there is ongoing work on other types of sensors for agriculture, including soil nutrient sensor [2], [50], [51], [52], plant emitted volatile organic compound gas sensors [53], [54], [50], and plant secreted metabolites [51].

III. SENSOR FOR IN-SITU IMPEDANCE MEASUREMENTS

Our previous work includes the design and testing of a dielectric measurement based soil impedance sensor that can make measurements at multiple frequencies (hence more accurate & reliable than single frequency measurement), is self-calibrating (hence robust), possesses wireless interface (hence can be located in-situ), and is also energy-efficient [26]. Sensing element which is a small metamaterial inspired patch is attached to this sensor as shown in the Fig. 2. 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. 3.

FIGURE 2. Sensor circuit inside the Package.

As a first step its measurement, the microprocessor programs the I2C inter-face 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 this range 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. The range of 1-40 MHz is sufficient for our application although same principle can be used to design a sensor with higher frequency range as well (using the PLL, demodulator and couplers that work for a higher frequency range).
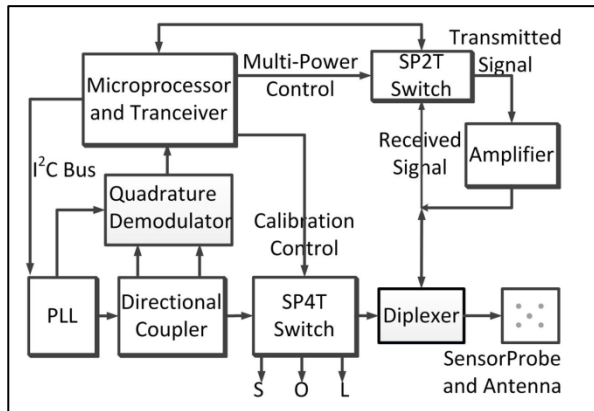
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FIGURE 3. Soil Sensor Architecture.

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 is shown in [23]. The accuracy of our in-situ sensor is confirmed against the measurements from lab equipment, a network analyzer, HP8714ESA. More than 90% accuracy over the range of 1-40 MHz in soil reactance was observed. This, together with the proof-of-concept of our ionic concentration sensing approach presented above, confirms that our own sensor can be used for estimating moisture and ionic concentrations in soil mixtures (of bulk soil, air, free and bound water, and ions) using dielectric spectroscopy to populate the mixing and relaxation models.

A prototype has been designed on a printed circuit board (PCB), packaged inside an acrylic box of dimension $2.5 \times 2.5 \times 1$ in^3. The package comprises of top and bottom

hollow acrylic blocks. The central hollow space holds the PCB and a battery. A coaxial cable connects the PCB to the metamaterial-inspired sensing element which is located on the outer surface of the top acrylic block. The metamaterial-inspired patch is designed to dual as an antenna (a key innovation) at a frequency different from sensing frequency, so the entire package can be buried underground where it can transmit data to a central station located above ground. As shown in Fig. 2, the package has a cutout on its outer surface to fit the metamaterial-inspired patch sensing-element cum antenna, so it remains exposed to the surroundings while battery and PCB are kept inside the package to keep them water proof. Acrylic box makes the sensor strong and durable. Due to non-degradable nature of acrylic, the sensor can survive underground. Also, our initial calculations of sensing and communication energy indicate an off-the-shelf battery life of at least 2 years. A more comprehensive discussion on the sensor can be found in [31].

IV. APPROACH

A dielectric mixture like soil comprises of a host material of certain dielectric constant, along with different scatters, with ith one having permittivity ϵ_i and fraction f_i, that are embedded in the host to form a mixture. We can treat the mixture as a macroscopically homogeneous under certain assumptions about shape, concentration, conductivity and orientation of these inclusions. Many derivatives of Maxwell-Garnett model have been developed in the past to explain the dielectric behavior of a mixture using dielectric constant of constituents and their concentrations. As discussed in previous section, Maxwell-Garnett mixing rule is one of the models which assume inclusions to be spherical and uniformly distributed in a host medium. The Maxwell-Garnett formula has been shown to work well for low concentrations of inclusions. However, when inclusion concentration becomes almost equal to the host, then a more symmetrical mixing model is needed. Such a mixing model has been proposed by Bruggeman (in which ϵ_{eff} denotes the mixture permittivity):

$$\sum_i f_i \frac{\epsilon_i - \epsilon_{eff}}{\epsilon_i + 2\epsilon_{eff}} = 0 \qquad (14)$$

A more generalized model [19] considers a mixture of n different types of ellipsoidal particles with different concentration, orientation, and distribution, mixed in a host. The proposed equation for effective mixture permittivity in this model is:

$$\epsilon_{eff} = \epsilon_{host} + \frac{\frac{1}{3}\sum_{j=1}^{n} f_j\left(\epsilon_j - \epsilon_{host}\right)\sum_i^3 \frac{\epsilon_{host}}{\epsilon_{host} + N_{ji}(\epsilon_j - \epsilon_{host})}}{1 - \frac{1}{3}\sum_{j=1}^{n} f_j\left(\epsilon_j - \epsilon_{host}\right)\sum_i^3 \frac{N_{ji}}{\epsilon_{host} + N_{ji}(\epsilon_j - \epsilon_{host})}} \qquad (15)$$

where f_j is the volume fraction of jth inclusion, N_{ji}'s are the depolarization factors of jth constituent along ith coordinate (value of the depolarization factor depends on the shape of the inclusion) and ϵ_j is the permittivity of jth constituent).

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As mentioned in previous section, all the above dielectric mixing models are quasi-static in nature, meaning that they hold well only for an electric field that varies slow enough to let the particles attain their equilibrium distribution for ionization and polarization. For sufficiently low frequencies at which the particle is much smaller than the wavelength, the quasi-static approximation can be used [18], [21], [41]. To use impedance measurements to infer ionic concentrations, we treat the soil as a homogeneous medium and various ions as inclusions embedded into this medium. Such homogenizing methods have been used in the past to obtain dielectric mixture models for soil [55].

Permittivity can be measured using the impedance measurements since the two are linearly related, such as in case of a metamaterial-inspired sensing element. Hence, accurate multi-frequency measurements of soil impedance can provide information about fractions of constituents of soil with known permittivity. From the above models, if the properties of individual constituents are known and an accurate measurement of the permittivity of the mixture is made, it is possible to calculate individual ionic concentrations. For a host mixed with n additional constituents, we need at least n equations in n unknown ionic concentrations. These n equations can be obtained by making n number of measurements of effective permittivity at multiple frequencies. For different frequencies, permittivity of individual ions also varies due to dielectric relaxation. Many such relaxation models like Debye relaxation, Havriliak-Negami relaxations etc. have been presented in literature [56]. Since individual permittivity vary with frequency, so does the effective permittivity of the mixture, and by measuring this variation over multiple frequencies it is possible to infer the concentration of n constituents present in the mixture.

V. EXPERIMENTAL SETUP AND MEASUREMENTS

A soil sample was collected from the top 0.50 m layer at the Iowa State University Agronomy Research Farm situated in Boone County, Iowa. (According to USDA published survey, Boone County predominantly has Loamy Wisconsin Glacial Till [57].) The soil was dried and collected in a rectangular container with 500 ml capacity (see Fig. 4) in order to make 5 different samples as detailed in next section. The metamaterial-inspired (see Fig. 5) patch was buried in the soil
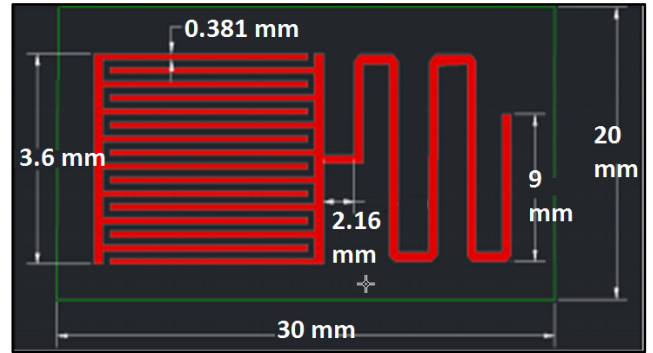
FIGURE 4. Experimental Setup for Impedance measurement.

FIGURE 5. Metamaterial inspired sensing element/antenna.

with a co-axial connector attached to it in order to measure the input impedance. In order to first establish a proof-of-concept of our approach, the impedance of the soil was measured at different concentrations of its constituents over a frequency range of 1- 40MHz using the Network Analyzer (HP8714ES). The results also help validate the measurements obtained from our own sensor (see Section VII).

Determination of Permittivity From Impedance: A lossless metamaterial-inspired patch of Fig. 5 can be equated to a transmission line comprising of distributed differential components as shown in Fig. 6.
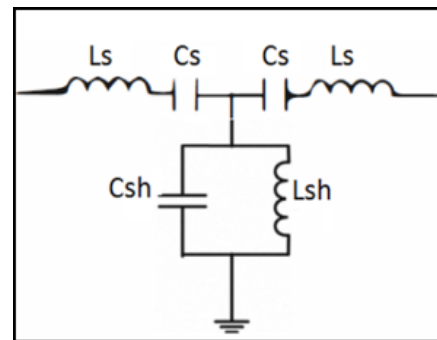
FIGURE 6. Unit cell structure for the metamaterial inspired antenna.

The series inductance represents the conductive material; series capacitance is due to inter-digitized capacitor while shunt capacitor and shunt inductances are due to separations and currents in the substrate and soil. At low frequencies however, the inductive part, being proportional to frequency, is very small compared to the capacitive part, which is inversely proportional to frequency, and can be ignored. This effectively implies that the patch is assumed to be a parallel plate capacitor. The capacitive energy is contained in 2 regions—in the substrate between two parallel layers and in the surroundings. The capacitance due to electric (E) field in the surroundings is known as the fringe capacitance and has been studied in the literature [58]. The capacitance of the substrate is given:

$$C_{ideal} = \epsilon_{sub} \frac{A}{D}, \quad (16)$$
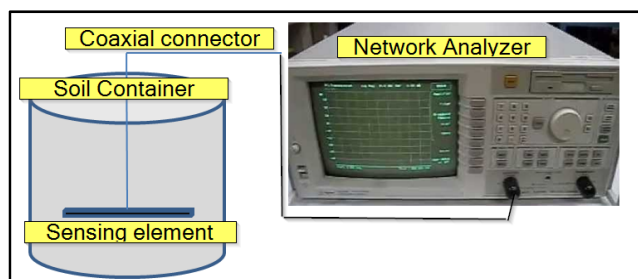
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where ϵ_{sub} is the substrate permittivity, A is the area of th parallel plates, and E is the distance between the plates. We are only interested in the fringe capacitance which is the capacitance due to soil mixture and can be viewed as a capacitor in parallel with the ideal parallel plate capacitor. The exact equation for the fringe capacitance is not needed and it suffices to know that the fringe capacitance is directly proportional to the surrounding permittivity. This is because the total energy stored in the fringe electric field is given by:

$$U = \frac{\frac{1}{2}\epsilon_{eff}}{2\pi} \int_V |E|^2 \, dV = \frac{1}{2}C_{soil}V^2, \qquad (17)$$

where V is the total potential difference between the plates. Since the input impedance comprises of 2 components— capacitance due to substrate and capacitance due to fringe field in the surroundings, we need to separate the two in order to obtain a single term that is proportional to surrounding permittivity and hence can be used directly in the models discussed in previous section. This can be achieved simply by making a measurement of the metamaterial-inspired patch capacitance and subtracting the value of its common substrate component from all the measurements. The resulting term does not contain the ideal parallel plate capacitance term and hence is independent of substrate permittivity and is also directly proportional to the surrounding permittivity.

VI. VARIATIONS IN CAPACITANCE AND CONDUCTANCE WITH VARYING NITRATE CONCENTRATION

Five measurements were performed on five soil samples. Different concentration of silver nitrate, 0 to 100 mM, in steps of 25 mM was added equaling 5% of the total volume of soil mixture used in experiment. The aim was to capture the variations in capacitance and conductance with chang- ing amount of solution and to explain the results in terms of dielectric mixing models discussed in previous sections. After adding the solution to the soil, the mixture was allowed to rest for 15 minutes so that the solution is absorbed well and the mixture becomes homogeneous within the limits of the experiment.

Due to high dissociation constant of silver nitrate $(AgNO_3)$, we assumed that all of the salt exists in ionic form, $Ag+$ and $NO3-$. Since each 25 ml addition of $AgNO_3$ increases the concentration of the ions as well as the water present in soil, the capacitance and conductance are both expected to increase proportionately. But due to factors such as non-uniform distribution of solution in soil, inter facial polarization, loss due to scattering and presence of magnetic impurities and ionic salts, the actual behavior is not exactly ideal.

At each frequency, the measurements were repeated three times and the average was calculated in order to minimize the effect of random noise affecting the measurements. The measured susceptance is shown in Fig. 7. It can be observed that for low concentrations of silver nitrate solution, the sus- ceptance (and hence capacitance) is almost same as that of dry soil. This implies that initial water added to soil doesn't

affect the capacitance in the same proportion as subsequent additions. This can be explained by the fact that initial water added to dry soil forms the bound water layer which does not polarize as fast as free water in presence of an external electric field. In addition, concentration of silver and nitrate ions is too small to affect significantly the capacitance. The conductance value shown in Fig. 8 shows an increasing conductance with increase in concentration of silver nitrate solution.
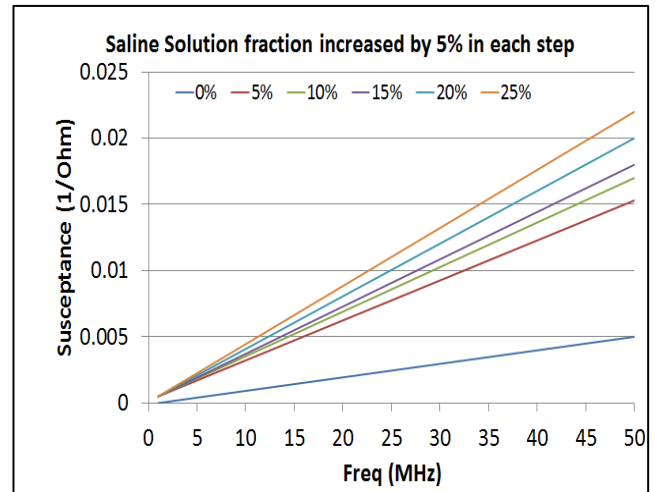

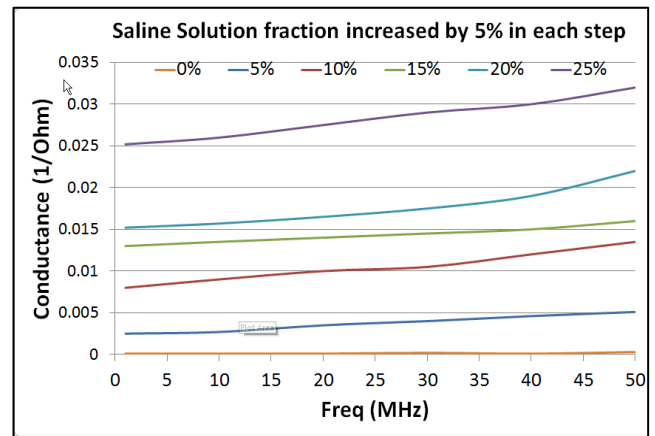**FIGURE 7.** Susceptance variation with moisture and nitrate change.

FIGURE 8. Conductance variation with moisture and nitrate change.

VII. ANALYSIS

Once silver nitrate solution is added to the soil, the permit- tivity of the soil starts to increase. This results in increasing capacitance and conductance of the soil dielectric mixture, as confirmed by Figs. 7 and 8, with some initial ''start-up'' phase for capacitance as explained above. We assume that the amount of soil bulk as well as air does not change during the course of the experiment (i.e. any swelling has negligible effect on soil-bulk fraction and air is merely displaced due to addition of solution). The fraction of soil-air mixture rep- resented by f_{soil} is merely reduced due to addition of nitrate

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solution. Then using the Bruggeman's symmetrical mixing rule, we have:

$$f_{soil}\frac{\epsilon_{soil} - \epsilon_{eff}}{\epsilon_{soil} + 2\epsilon_{eff}} + f_{sol}\frac{\epsilon_{sol} - \epsilon_{eff}}{\epsilon_{sol} + 2\epsilon_{eff}} = 0 \quad (18)$$

$$f_{soil} + f_{sol} = 1 \quad (19)$$

where f_{sol} is the fractional volume of solution added. Note again that each permittivity term is a function of frequency and is assumed to follow the Debye relaxation model mentioned in Equation (11).

According to the discussion in [21] on lossy inclusions in lossless background dielectric mixtures, if the imaginary part of the permittivity of inclusion is much smaller than the real part, then the effective permittivity is indistinguishable from the corresponding material with equivalent real permittivity but no imaginary permittivity. This essentially implies that for low loss inclusions, the dielectric mixing formulas give close results even if only the real part of permittivity is considered. We make use of this fact to estimate the concentration of the silver nitrate solution for which real part of permittivity is close to that of water (water 80) while imaginary part, that is essentially the conductivity of silver nitrate divided by the angular frequency, is considerably small [5]. The electric field due to the parallel plates of the patch is present in the substrate as well as surroundings. The capacitance due to substrate is a fixed value and needs to be subtracted from overall capacitance in order to get a value that is proportional to the surrounding permittivity. It has been discussed in [10] that the capacitance due to fringe field in air is approximately 3 times that of substrate capacitance for the aspect ratio that has been used in our experiment (3:5). The fixed value of capacitance can thus be approximately estimated by taking a quarter of the capacitance measured with air as surrounding. Accordingly, the estimated fraction of solution is shown in Fig. 9 and compared with the actual amount of solution added. There is an accuracy of at least 85%.
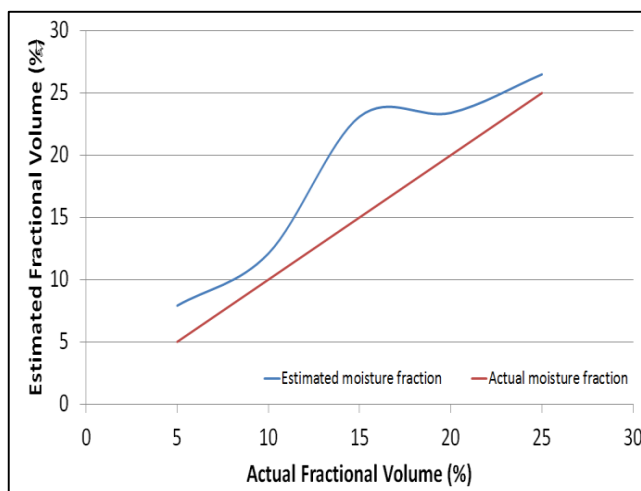
The conductivity of a dielectric mixture has been shown to increase with increasing concentration of saline solution. The conductance of soil dielectric mixture is proportional to the imaginary part of dielectric permittivity. For a dielectric mixture with saline solution as a constituent, all the conductivity 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 silver nitrate is shown in Fig. 10. 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.
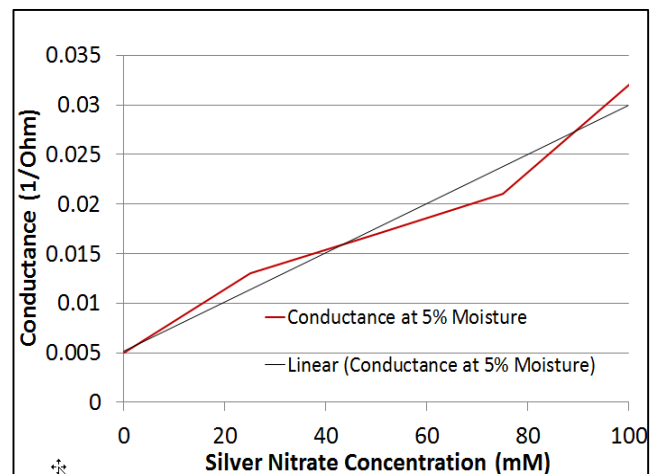

FIGURE 10. Estimation of silver Nitrate fractional volume.

VIII. CONCLUSION AND DISCUSSION

Using the multi-frequency impedance measurement approach, a method for estimating the in-situ nitrate concentration in soil by analyzing dielectric mixture models over mixture of Debye-type constituents is developed. We demonstrate that the conductance of soil dielectric mixture varies linearly with concentration of ions present. Metamaterial-inspired patch is shown to act as a good sensing element for the frequency range of 1-40 MHz. The results of ionic concentrations derived from impedance measurements applying our approach were compared against the actual values and an accuracy of 90% was found over 1-40 MHz frequency range, which is adequate for precision agriculture applications. The approach may be extended to measure ionic concentrations in a mixture of multiple ions by accounting for the contributions of different ions into the overall conductivity that is a function of fraction, valence and mobility (which also depends

FIGURE 9. Estimation of saline water fractional volume.

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on frequency). This is a direction for future research. Due to the capability of the sensor to communicate, multiple sensors cab be easily integrated to aide precision agriculture. Knowledge of amount of moisture and ions present in the field at a given time can help us determine whether more fertilizer or moisture needs to be added to the soil and at which locations. Thus, increased resource utilization and minimized environmental effects can be achieved. This can provide huge benefits in soil fertilizer management and can provide significant agricultural and environmental benefits.

While in Section VI we presented a physics-based approach, an empirical approach may also be developed, as discussed in the following:

A. EMPIRICAL ESTIMATION OF MOISTURE AND IONS

Moisture and ionic contents are directly related to the imaginary and real part of impedance that is measured using
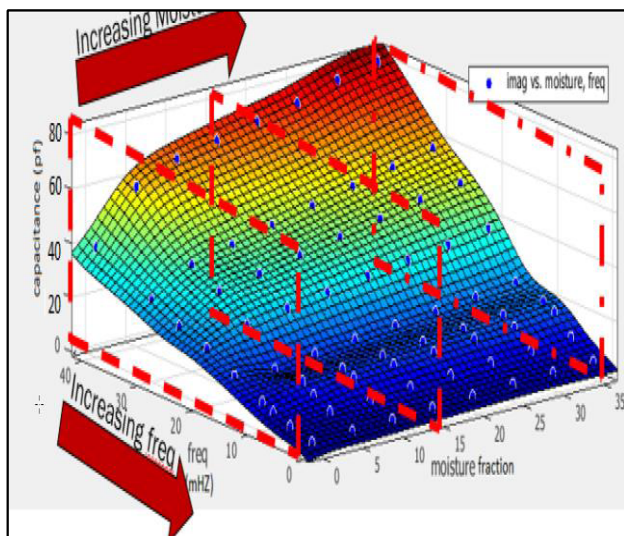
the sensor:

$$capacitance_i = g\,(freq_i, \%moisture) \tag{20}$$

$$conductance_i = h\,(freq_i, salinity) \tag{21}$$

Here, the mapping function g and h are estimated using curve-fitting in MATLAB (using the command *cftool*) by measuring capacitance and conductance values at known frequency and moisture and ionic values. In Fig. 11, the capacitance values are curve-fitted to at 6 different moisture values and 10 different frequency values at each moisture value. For any unknown amount of moisture, if we measure capacitance at multiple frequencies, least-square estimate of the moisture can then be generated by minimizing with respect to percentage moisture the cumulated square of the error across multiple frequencies:

$$\min_{\%moisture} \left[\sum_i capacitance_i g\,(freq_i, \%moisture) \right]^2 \tag{22}$$

A similar 3-dimensional curve-fitting was performed for salinity as shown in Fig. 12.

FIGURE 11. Capacitance as a function of frequency and moisture content.
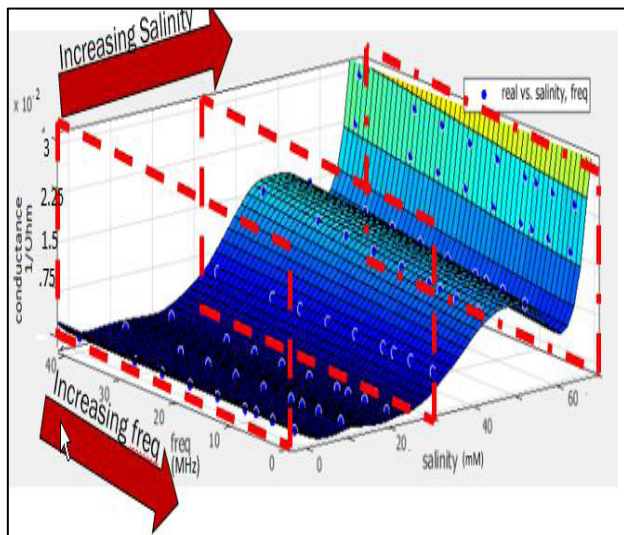
FIGURE 12. Conductance as a function of frequency and salinity content.

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