A Multi-frequency, Self-Calibrating, In-Situ Soil Sensor with Energy Efficient Wireless Interface

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ABSTRACT
Real time and accurate measurement of sub-surface soil moisture and nutrients is critical for agricultural and environmental studies. This paper presents a novel on-board solution for a robust, accurate and self-calibrating soil moisture and nutrient sensor with inbuilt wireless transmission and reception capability that makes it ideally suited to act as a node in a network spread over a large area. The sensor works on the principle of soil impedance measurement by comparing the amplitude and phase of signals incident on and reflected from the soil in proximity of the sensor. Accuracy of measurements is enhanced by considering a distributed transmission line model for the on-board connections. Presence of an inbuilt self-calibrating mechanism which operates on the standard short-open-load (SOL) technique makes the sensor independent of inaccuracies that may occur due to variations in temperature and surroundings. Moreover, to minimize errors, the parasitic impedances of the board are taken into account in the measurements. Measurements of both real and imaginary parts of soil impedance at multiple frequencies gives the sensor an ability to detect variations in ionic concentrations other than soil moisture content. A switch-controlled multiple power mode transmission and reception is provided to support highly energy efficient medium access control.1

1. INTRODUCTION
Efficient management of agricultural resources for increased productivity and minimum environmental impact forms the basis of precision agriculture. In a generic precision agriculture layout (see Figure 1), intra- and inter-field variabilities are characterized using a network of sensor nodes spread over a large area. Each sensor node sends local information about the properties of the soil surrounding it. All the information collected is sent to a central node which processes the information and takes necessary measures like irrigation and fertilization. Thus, each node in this sensor network not only measures the soil content accurately in real time, it also communicates efficiently with other nodes in the network in order to transmit the collected information.

This paper presents an on-board solution for a sensor which can measure local soil conditions like water as well as ion content with high accuracy. It also has the capability to sweep through a frequency range to improve the data reliability of moisture and ionic content measurements. To achieve high accuracy and robustness of measurements, the sensor has a built-in self-calibrating system which is based on embedded measurements of open, short and matched load conditions. For efficient transmission, a built-in multi-power mode is introduced in transmission and reception. Such system has been shown to support more energy-efficient medium-access-control (MAC) protocol.1 The main contributions of this work can be summarized as:
1. The sensor has the capability to measure impedance at multiple frequencies. This improves accuracy and also gives the sensor the ability to detect multiple ions.2
2. The sensor has a built-in self-calibration system which makes them impervious to the variations in soil temperature and climatic conditions like hail, drought, rain etc.
3. The sensor is designed for in-situ underground operation through an in-built antenna and wireless transceiver, so as not to interfere with the above ground operations. To economize on size, the sensor probes are diplexed to act as antenna.

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Figure 1. Conceptual Layout of a Soil Sensor network.

4. The built-in transceiver has multiple power modes for transmitter/receiver to support a highly energy efficient MAC (Medium Access Control).  

Spectral dielectric sensing also has the potential to detect pathogens and undesired microbial growth whose presence changes the electric properties of the sample. Such spectroscopic dielectric sensing has been shown to be useful in detecting the presence of bacteria such as E-coli after incubation with appropriate anti-microbial peptides (AMP). Microcapacitive sensors based on similar principle have shown direct proportionality between impedance changes due to change in the dielectric properties and the extent of analyte binding occurring on the surface of an electrode.  

2. BACKGROUND  

Many attempts have been made to accurately measure varying moisture levels in the soil. Notable approaches found in literature for soil-moisture measurement include thermal sensors, neutron probe sensors, granular matrix/gypsum block sensors, TDR/FDR based impedance measuring electronic sensors, Some of them are discussed here.

Thermal sensors determine the properties of the soil using the thermal properties like conduction and radiation. They are based on the principle that soil thermal properties vary with change in the moisture level and hence a measure of moisture content can be obtained by observing the change in these properties. Thermal Sensors determine moisture content using these two methods (heat conduction and heat radiation). The heat conduction method uses a heater and temperature sensor separated by a distance and the temperature change in the soil is measured to determine the amount of moisture present. Heat radiation method uses a heater and two thermo couples-one of which is attached to the radiation plate connected to the heater and second is placed on a patch attached to an aluminum plate kept at a distance from the heater. The temperature curves of thermocouples are then observed to see the thermal characteristic of the medium. Another thermal pulse sensor generates heat pulse whose durations and magnitude is controlled by a microprocessor. This heat pulse changes the voltage across the thermistor. The change in voltage across the thermistor is related to the moisture content by using the empirical relations. One inherent disadvantage of using a thermal sensor is that the installed heater can affect the moisture concentration around the sensor node causing evaporation and hence accurate measure of soil content may not be determined. Also, due to the agricultural activities carried out in the soil, the thermal properties might change due to factors other than moisture. Some examples can be addition of fertilizers and loosening of soil due to ploughing. Hence a periodic calibration is needed.

Another approach used to measure soil moisture is to use a satellite system which can remotely measure the moisture content by GNSS-R (Global navigation satellite system reflection) signal. Each sensor node has two antennae one of which points to the ground and other to the satellite. The sensor measures the reflectivity of
the soil, which primarily depends on the moisture content. This information is sent to the satellite and a global data can be collected through a series of such sensor nodes. Since the nodes are placed above the ground and the depth to which a wave can travel is limited by the losses in the soil, this method does not necessarily provide actual moisture level which is available to the roots of the crops. GPR (ground penetration radar) based method is also used for soil sensing.\textsuperscript{15} Using the Debye model for relaxation time of water molecules it is argued that the amount of water will affect the scattering characteristics of the signal reflected from the ground. Hence, the frequency spectrum of the received signal will give an indication of the water content present in the soil. Satellite based sensors can provide good accuracy, but spatial resolution is limited.

A granular matrix based approach to the soil moisture sensing has been described in literature.\textsuperscript{7} The sensor operates on the electrical resistance principle and is made of porous ceramic material as external shell. Two electrodes are inserted in the internal matrix. As water content in the soil varies, the amount of water seeping in through the porous shell also changes. This changes the electrical resistance between two electrodes which can be monitored. Sensor contains a wafer of gypsum to protect the electrodes against salinity in the soil. An NIR (Near Infra-Red) spectrometer\textsuperscript{16} is another type of sensor. The spectrophotometer is attached to the back of the subsoiler chisel to perform light reflectance measurement from the soil surface. The calibration is done under laboratory condition. This method is highly expensive due to sophisticated components involved. Also the measurement is done only while using the chisel which may not be required at all times.

A neutron probe based soil sensor has also been developed.\textsuperscript{6} The authors provide computer modeling and testing for the neutron sensor which will work for top 15 cm of soil. In a neutron probe sensor, fast neutrons are emitted from a decaying source into the soil where they bounce around and gradually slow down in the process mainly due to collisions with the hydrogen nuclei in the surroundings. Thermal and epithermal probes detect a fraction of these moderated neutrons depending on the concentration of hydrogen nuclei in the surroundings. In most soils, the only source of hydrogen would be water which means that the slowing down of fast neutrons would be due to water. These sensors, although very accurate, are more suited for reactor sites where radioactivity is not a problem. These are expensive due to cost of neutron probe and detector.

Impedance Sensors are a common type of sensors which have the potential to get rid of most of the inherent disadvantages which are present in thermal, granular matrix, neutron probes and remote no-contact sensors. Some of the advantages offered by impedance sensors are their ability to make measurements in real time, ease of sensor calibration, no effect of sensor on surrounding soil properties, no interference of sensor in agricultural processes, accuracy and ease of measurement. Moreover, impedance sensors can naturally form a part of a circuit which can include a transceiver and hence they can easily be embedded into a network. This further means that they are controllable from a remote station. These sensors can be calibrated to work for different types of soil and they work for large range of moisture content. The downside of impedance sensors is increased complexity. Moreover, all electrical circuits come with a certain amount of noise which affects accuracy. Many different types of impedance sensors are present in the literature. Fringing electric fields have been used\textsuperscript{17} to determine the permittivity of soil under observation. The experimental setup discussed uses a fringing capacitance followed by the FEM (finite element method) analysis to relate capacitance with permittivity. Variations in moisture content changes the permittivity which in turn changes the capacitance that can be detected. The setup lacks a self-calibration algorithm and requires measuring capacitance and permittivity for known moisture content from time to time. This is not practical specially for a large network of buried autonomous sensor nodes. The study has not been extended to analyzing nutrients besides moisture.

Another frequency domain approach has been suggested based on capacitive sensing.\textsuperscript{11} Like in previous discussion,\textsuperscript{17} a fringing field capacitance is used to project the sensing electric field into the surrounding material. An AC (Alternating Current) signal applied to this capacitor will shift its phase depending on equivalent RC model of capacitance. The phase shift has been shown to be proportional to $\sin^{-1}$ of the capacitance value. The driving signals follows two paths- one direct and another through soil container- to the phase detector. It is assumed that the only phase shift will occur in the soil containing capacitor which is a fair assumption given proper fabrication is done. Thus phase shift can be used to find capacitance which in turn can be used to determine dielectric constant of soil contained in the capacitive cell. Since, different frequencies will result in different phase change across the capacitor, calibration is needed every time the frequency is changed. Hence a multi-frequency implementation of this work becomes more complicated. FDR approach has also been used\textsuperscript{18} to
develop an ASIC (Application Specific Integrated Circuit) to measure the capacitance which has been mapped to permittivity and soil moisture. The sensor shows good accuracy and permittivity resolution.

Time Domain Reflectometry (TDR) has inspired many past and ongoing sensor designs. The basic idea is to direct a square pulse towards a soil sample and calculate the coefficient of reflection at the surface from which the wave gets reflected. The reflection coefficient along with the characteristic impedance of the line gives the impedance of the surface at which reflection takes place. Creation of the dielectric profile for the soil using TDR has been discussed in literature.\(^9\) For the measurement of spatially resolved dielectric profiles by using delay time measurements, a transmission line is used. The delay time of an electromagnetic pulse along the transmission line is measured with the help of an industrial TDR system operating in the baseband up to 3 GHz with a pulse width of 300 ps. A phase-shift based approach for finding unknown impedance using TDR has also been discussed.\(^19\) Phase shift in traveling wave along the length of transmission is proportional to the square root of permittivity. Thus knowing the phase shift gives the value of permittivity of the medium. In situ application of this method requires a high cost of TDR system. TDR method has additional drawbacks such as problems with extracting accurate parameters from the received waveforms, difficulties in detecting the reflected signal in saline soils, and dependence of measurement on the coaxial cable and probe lengths.\(^15\)

To summarize, there is a definitive need for a sensor system which gives accurate results at multiple frequencies, is self-calibrating, can be part of a network, consumes small amount of power and is relatively less expensive. Our approach involves reflection as in TDR systems, but instead of measuring the time delay or phase shift we measure the amplitude and phase of incident and reflected waves. This is beneficial for real time sensing as the surface under observation can be outside of the system unlike capacitive sensors\(^11\) which needs waves to travel through the conductor contained in the line. Our system has the capability to make measurements at multiple frequencies and is self-calibrating which makes it more robust, more accurate and low maintenance. Like capacitive measurement schemes used in\(^17\) and,\(^11\) our system measures unknown impedance. Its measurements are based on reflectometry allowing us to make a direct correlation between impedance and permittivity. 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.\(^2\) Using de-embedding techniques, some of the disadvantages related to TDR sensors like inaccurate measurements due to probe length have been removed.

### 3. APPROACH

The problem of measuring soil moisture content can be broken down broadly into three steps:

1. Measuring the unknown impedance of sensor which is embedded in the soil whose properties are to be determined;
2. Calculating the permittivity of soil using the measured impedance value;
3. Determining the soil moisture content from the permittivity values.

If a transmission line with characteristic impedance \(Z_0\) is terminated in a load impedance \(Z_L\), then the coefficient of reflection is defined as:\(^20\)

\[
\Gamma_L = \frac{V_r}{V_i} = \frac{Z_L - Z_0}{Z_L + Z_0}.
\]

\(V_r\) and \(V_i\) are signals reflected from and incident upon the load impedance respectively (see Figure 2). For a microstrip transmission line, \(Z_0\) is a constant and depends on the width of the transmission line and permittivity of the pcb substrate. We have designed \(Z_0\) to be 50 ohms. Thus, if we make accurate measurements of \(V_r\) and \(V_i\), we can calculate the value of \(Z_L\). To measure \(V_r\) and \(V_i\), we need to measure amplitudes and phases of \(V_r\) and \(V_i\). To make these measurements, incident and reflected signals, which are on the same transmission line, have to be separated. This can be done efficiently using a pair of directional couplers. A directional coupler is a device that can be used to couple a small fraction of the signal flowing in a particular direction on a transmission line to its output port. The signal flowing in other direction is not coupled. Two directional couplers are connected to the main line as shown in Figure 2. One coupler couples the incident signal, while the other couples the reflected signal to its output port.

Since on-board couplers are not point objects, there always is a finite distance between point at which load is connected to the line and the point where signal coupling takes place. This means that the coupled signals
at ports 3 and 4 are gain/phase shifted relative to the incident signal, \( V_I \) and reflected signal, \( V_r \) respectively. Since this shift depends on the frequency and the length of the transmission line between the coupler and the load impedance, this shift can be accounted for by proper calibration. In order to find a relationship between the ratio of reflected and incident signals (\( \Gamma_L = \frac{V_r}{V_I} \)) at the load and the ratio of coupled reflected and incident signals at the ports 4 versus 3 (\( \Gamma_m = \frac{V_4}{V_3} \)), we treat the combined system of two couplers and the transmission line as a four port network, with the ports numbered as shown in Figure 2, where the source is port 1 and the load is port 2; port 3 couples with the incident signal and port 4 couples with the reflected signal. Owing to the fact that the outputs and inputs of such a 4-port network are linearly related, it has been shown\(^{20}\) that the measured value of reflection coefficient, \( \Gamma_m \) and the reflection coefficient at the load, \( \Gamma_L \) are related by a bilinear transformation:

\[
\Gamma_m = \frac{V_4}{V_3} = a \Gamma_L + b \Gamma_L + 1 \quad (2)
\]

where \( a, b \) and \( c \) are constants for this 4-port network while \( V_4 \) and \( V_3 \) are output voltage signals from port 4 and port 3 respectively. This implies that 3 measurements of \( \Gamma_m \) at three different loads (or equivalently three different \( \Gamma_L \)'s) will give us 3 equations in 3 unknown calibration constants \( a, b \) and \( c \). For ease of calculation we can chose these three known load impedances to be \( \infty \) (open-circuit), 0 (short-circuit) and \( Z_0 \) (matched load), with the corresponding load reflection coefficients \( \Gamma_L \) being 1, -1 and 0 respectively. The equations in 3 unknowns can be solved by solving the matrix:

\[
\begin{bmatrix}
\Gamma_{L1} & 1 & -\Gamma_{L1}\Gamma_m1 \\
\Gamma_{L2} & 1 & -\Gamma_{L2}\Gamma_m2 \\
\Gamma_{L3} & 1 & -\Gamma_{L3}\Gamma_m3
\end{bmatrix}
\begin{bmatrix}
a \\
b \\
c
\end{bmatrix}
= 
\begin{bmatrix}
\Gamma_m1 \\
\Gamma_m2 \\
\Gamma_m3
\end{bmatrix}
= 
\begin{bmatrix}
a \\
b \\
c
\end{bmatrix}
= 
\begin{bmatrix}
\Gamma_{L1} & 1 & -\Gamma_{L1}\Gamma_m1 \\
\Gamma_{L2} & 1 & -\Gamma_{L2}\Gamma_m2 \\
\Gamma_{L3} & 1 & -\Gamma_{L3}\Gamma_m3
\end{bmatrix}^{-1}
\begin{bmatrix}
\Gamma_m1 \\
\Gamma_m2 \\
\Gamma_m3
\end{bmatrix}
.
\]

The constants \( a, b, c \) can then be calculated using:

\[
\begin{bmatrix}
a \\
b \\
c
\end{bmatrix}
= 
\begin{bmatrix}
\Gamma_{L1} & 1 & -\Gamma_{L1}\Gamma_m1 \\
\Gamma_{L2} & 1 & -\Gamma_{L2}\Gamma_m2 \\
\Gamma_{L3} & 1 & -\Gamma_{L3}\Gamma_m3
\end{bmatrix}^{-1}
\begin{bmatrix}
\Gamma_m1 \\
\Gamma_m2 \\
\Gamma_m3
\end{bmatrix}
.
\]

Once we know the values \( a, b \) and \( c \), we can use these values and the measurement of \( \Gamma_m \) to infer

\[
\Gamma_L = \frac{b - \Gamma_m}{c\Gamma_m - a},
\quad (3)
\]

when an unknown impedance is presented as the load. This value of \( \Gamma_L \) can then be used to calculate the unknown load \( Z_L \), by applying Equation 1.

Figure 2. Directional Coupling of incident and reflected signals.
3.1 Design of Amplitude and Phase Measurement System

For accurate measurement of $\Gamma_m$, it is important to make an accurate noise free measurement of $V_{o4}$ and $V_{o3}$. $V_{o4}$ and $V_{o3}$ are signals of a certain pre-determined frequency, $\omega$. These signals can be sent as input to a Quadrature Demodulator. A quadrature demodulator is essentially a pair of mixers which multiplies its input by a pair of sinusoids that are identical except their phases are 90 degrees apart, $S_1 = S_0 \cos(\omega t)$ and $S_2 = S_0 \sin(\omega t)$. Letting $V_{o k} = V_{k0} \cos(\omega t + \phi_k)$ denote the port-$k$ output ($k = 3, 4$) that is fed as input to the quadrature demodulator (see Figure 3), we have:

$$S_1 * V_{o k} = \frac{S_0 V_{k0}}{2} (\cos(\phi_k) + \cos(2\omega t + \phi_k)),$$

$$S_2 * V_{o k} = \frac{S_0 V_{k0}}{2} (\sin(\phi_k) + \sin(2\omega t + \phi_k)).$$

On low pass filtering these two mixer outputs, high frequency terms are rejected and the two outputs are the in-phase component:

$$I_k = \frac{S_0 V_{k0}}{2} (\cos(\phi_k)),$$

and the quadrature-phase component,

$$Q_k = \frac{S_0 V_{k0}}{2} (\sin(\phi_k)).$$

Then the ratio of amplitudes of $V_{o4}$ and $V_{o3}$ is calculated using:

$$\frac{V_{o4}}{V_{o3}} = \sqrt{\frac{I_4^2 + Q_4^2}{I_3^2 + Q_3^2}}.$$  \hspace{1cm} (6)

The phase difference $\phi_4 - \phi_3$ is given by:

$$\phi_4 - \phi_3 = \tan^{-1}(\frac{Q_4}{I_4}) - \tan^{-1}(\frac{Q_3}{I_3}).$$  \hspace{1cm} (7)

The outputs of the quadrature demodulator are received by the microprocessor through an inbuilt Analog to Digital Converter (ADC). The microprocessor performs the calculations stated above to accurately determine $\Gamma_m = V_{o4}^2 / V_{o3}^2$. While calibrating, it uses these values to calculate the coefficients $a, b$ and $c$ using the matrix-based computation discussed in previous section. While measuring the unknown load, it uses the $a, b, c$ coefficients to find out the reflection coefficient $\Gamma_L$ for the unknown load using Equation 3. The $\Gamma_L$ value is then used to determine the unknown load impedance $Z_L$ using Equation 1. For quadrature demodulation, AD8333 from analog devices has been used.
3.2 Design of Self-Calibration System

As seen in previous section, for sensor calibration we need the measurements on a set of 3 known impedances in order to account for the non-colocation of the load impedance and the coupler output ports. In order to make the sensor a self-calibrating system, we have designed a self-calibrating mechanism using a Single-Pole-4-Throw (SP4T) switch. An SP4T switch has a 2 bit control signal which controls the connection of input RF port to one of the 4 output ports (see Figure 4). The control signal is programmed by the microprocessor at the beginning of each sensing event to cycle through all the four values. Once the control signal has swept through the values 00 (open-circuit), 01 (short-circuit) and 10 (matched-load), we calculate the calibration constants $a$, $b$, and $c$. For the measurement of unknown impedance, the control signal is changed to 11. Using the $\Gamma_m$ for this measurement and calculated $a$, $b$, $c$ values, we calculate $\Gamma_L$ which is then used to calculate $Z_L$.

3.3 Multi-Power modes in transceiver

An energy-efficient MAC\(^1\) can be implemented if an additional higher power transmission mode, called ping, and an additional lower power receiver sensitivity mode, called drowsy is included (besides the usual normal and sleep modes). This can be implemented by using a system shown in Figure 5, where a Single-Pole-2-Throw (SP2T) switch is placed in between the transceiver and the antenna. During a transmission in the ping mode, the SP2T connects the transmitter to a power amplifier which amplifies the signal by 15 dB before feeding it to the antenna. During reception, the SP2T feeds the signal directly to the receiver, bypassing the power amplifier. Besides, the off-the-shelf transceiver CC1110 from Texas Instruments that we use already has an in-built receiver with the additional drowsy mode for a “low-powered listening” during wake-up synchronization as initiated by the generation of a “high-powered ping” by a neighboring node.\(^1\)

3.4 Electrodes Diplexed to Act as Antenna

Once the microprocessor has the soil impedance measurement, it needs to transmit it to the receiver. For this purpose, and to reduce the size of the sensor node, we have designed the sensor electrodes to double up and act as an antenna with the help of a diplexer. A quarter wavelength monopole antenna at 433 MHz frequency is approximately 17 cm in length and has been mounted as a center prong on a copper ground plane. Apart from this center prong that acts as a monopole antenna mounted on a copper ground plane, there are 4 more prongs surrounding the central prong (see Figure 6) which act as the ground pins for the antenna as well as the sensor electrode. In this 5 prong sensor, the center prong acts as the antenna at the transmission frequency of 433 MHz and as the positive electrode at the sensing frequencies of 1 MHz to 30 MHz. The remaining 4 prongs act as the ground in the antenna and as the negative electrode in the sensor measurements. Since the transmission and the sensing occur at two different frequencies, 433 MHz versus 1-30 MHz respectively, it is possible to separate the two frequency paths using a diplexer (see Figure 7). A diplexer has a low pass path with the transmission...
frequency in its pass-band and the minimum sensing frequency in its stop-band. It also has a high pass path with the transmission frequency in its stop band and the minimum sensing frequency in its pass band.

4. COMPLETE SENSOR ARCHITECTURE

The complete sensor architecture consisting of microprocessor, transceiver, phase-lock-loop (PLL) for sinusoid generation, directional coupler, quadrature demodulator, SP4T and SP2T switches, power amplifier, low-pass filter and diplexer is as shown in Figure 8. When the system starts, the first step by the microprocessor is to program the PLL to the desired frequency of operation. The microprocessor, that also has an inbuilt transceiver, is CC1110 from Texas Instruments. In the first step, the $I^2C$ interface of the programmable PLL (CDC903 from Texas Instruments) is programmed to generate 2 frequencies $\omega_1$ and $\omega_2$ with $\omega_2 = 4\omega_1$. The $\omega_1$ signal is sent through the transmission line towards the SP4T switch. The $\omega_2$ ($= 4\omega_1$) signal is sent to the quadrature demodulator which internally converts these signals to 2 signals $S_1$ and $S_2$ that are at 90° phase difference from each other. These signals are used by the quadrature demodulator to convert the outputs of the couplers into in-phase and quadrature-phase components as explained in Section III. The SP4T switch which is used for calibration gets its control bits from the microprocessor. In the calibration mode, a sequence of 00, 01 and 10 is sent to the SP4T switch. Thus, the transmission line is connected to open, short and matched load in the consecutive cycles of SP4T switching control signal. Once calibration is completed the control signal is set to
The incident and reflected waves are coupled to the output ports of the directional couplers located along the transmission line. The output signals are passed on to the inputs of a quadrature demodulator. The quadrature demodulator performs the mixing with in-phase and quadrature-phase signals, and the result is low pass filtered to get the DC outputs consisting of the in-phase and quadrature-phase components. The outputs of the low-pass filter are received by the microprocessor through an in-built 12-bit ADC (Effective number of bits is 10.8). The microprocessor calculates Amplitude and Phase of the incident and reflected waves. In the calibration mode, these values are used to calculate the coefficients $a$, $b$ and $c$ using the matrix method discussed in the previous sections. In the measurement mode, it uses these coefficient values to find out the reflection coefficient $\Gamma_L$ for an unknown load. The $\Gamma_L$ value is then used to determine the unknown impedance $Z_L$ using Equation 1.

5. EXPERIMENTAL VALIDATION

A cylindrical fixture was constructed using acrylic material to hold the soil with the 5-prong sensor embedded into the soil (see Figure 9). To connect the sensor to the on-board circuit, the fixture was fitted with an SMA (Sub-Miniature version A) port at the top whose one end was connected to the SP4T switch mounted on the pc board and the other end, which is interior to the cylindrical fixture, was connected to the 5-prong sensor/antenna. The cylindrical fixture with 5-prong sensor inside was filled with the clarion loam soil that was collected from the top 0.50 m layer at the Iowa State University Agronomy Research Farm situated in Boone County, Iowa. The soil impedance was measured by the on-board sensor that we designed and for comparison of its accuracy also by a Network Analyzer (HP8714ES). This 5-prong sensor with soil contained between the prongs, acts as the unknown load as discussed in Section III. The data recorded by the on-board circuit is transmitted to a receiver which first calculates the $a$, $b$ and $c$ calibration constants and then calculates the soil impedance using Equations 1 and 2. The real and imaginary parts of impedance measured using the on-board sensor showed a good match with those measured using the network analyzer in the range 1-30 MHz (see Figures 10 and 11).

6. CONCLUSION AND DISCUSSION

An on-board architecture for an in-situ, wireless, energy-efficient, robust, accurate and self-calibrating soil moisture and nutrient sensor with inbuilt wireless transmission and reception capability has been presented, designed, fabricated and validated. The on-board sensor was shown to have good accuracy which was comparable to a Network Analyzer. The accurate multi-frequency measurements on soil impedance can provide information not only about soil moisture content but also about other ionic concentrations. One way to use impedance measurements to obtain ionic concentrations is by treating the soil as 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.\textsuperscript{21} A generalized model proposed\textsuperscript{21} considers a mixture of \( n \) different types of ellipsoidal particles with different concentration, orientation and distribution that are embedded in a host with permittivity \( \epsilon_{\text{host}} \). The proposed equation for effective mixture permittivity, \( \epsilon_{\text{eff}} \), in this model is:

\[
\epsilon_{\text{eff}} = \epsilon_{\text{host}} + \frac{\frac{1}{3} \sum_{j=1}^{n} f_j (\epsilon_j - \epsilon_{\text{host}}) \sum_{i=1}^{3} \frac{N_{ji}}{\epsilon_{\text{host}} + N_{ji}} \left( \epsilon_j - \epsilon_{\text{host}} \right)}{1 - \frac{1}{3} \sum_{j=1}^{n} f_j (\epsilon_j - \epsilon_{\text{host}}) \sum_{i=1}^{3} \frac{N_{ji}}{\epsilon_{\text{host}} + N_{ji}}} ,
\]

where \( f_j \) is the volume fraction of \( j^{\text{th}} \) inclusion, \( N_{ji} \)'s are the depolarization factors of \( j^{\text{th}} \) component along \( i^{\text{th}} \) coordinate (they depend on the shape of the inclusion) and \( \epsilon_j \) is the permittivity of \( j^{\text{th}} \) component. From the above model, if the properties of individual constituents are known and an accurate measurement of permittivity of the mixture is made, it is possible to calculate individual ionic concentrations. For a host mixed with \( n \) additional components, we need atleast \( n \) equations in \( n \) unknown ionic concentrations. These \( n \) equations can be obtained by making \( n \) number of measurements of \( \epsilon_{\text{eff}} \) at a fixed or multiple frequencies. For different frequencies, permittivity of individual ions also varies due to dielectric relaxation. Many such relaxation models like debye relaxation, Havriliak-Negami relaxation etc are present in literature.\textsuperscript{22} Debye relaxation model is given by the equation:

\[
\epsilon = \epsilon' + j\epsilon'' = \epsilon_\infty + \frac{\epsilon_0 - \epsilon_\infty}{1 + j\omega\tau} ,
\]

where \( \epsilon_0 \) the permittivity of the molecule at very low frequencies, \( \epsilon_\infty \) is the permittivity at very high frequencies and \( \tau \) is the relaxation time which is defined as the time required by the molecular dipole to reach new equilibrium when a time varying external Electric field is applied. Thus for each frequency, permittivity of individual ions can be determined using dielectric relaxation models. The in-situ soil impedance sensor described above has the ability to make measurements of soil permittivity from 1 MHz to 30 MHz. Dependence of nitrate and chlorides on soil permittivity has previously been demonstrated through laboratory work\textsuperscript{2} using multi-frequency dielectric spectra from 1-14 MHz. Thus, using our sensors, it is possible to determine individual ionic concentration by applying the classic dielectric mixing and relaxation models combined with permittivity measurements at different frequencies. Nutrients/ions sensing based on the about outlined principles is a part of our ongoing effort and the findings will be reported as part of a future work.

REFERENCES


