A Folded Monopole Shaped Novel Soil Moisture and Salinity Sensor for Precision Agriculture Based Chipless RFID Applications

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Abstract— This paper focuses on the design and analysis of an inexpensive novel chipless RFID sensing scheme for soil moisture and salinity content detection. The sensor is designed at the UHF RFID band so that it can be tweaked easily to a chip-based RFID sensor. Alongside the designed sensor, a theoretical soil model with different moisture and salinity levels is simulated here. A fabricated prototype is used to measure the variation of moisture and salinity levels in sandy soil. Both the simulated and measured results exhibit frequency shift of sensor resonance with moisture content variation at non-saline conditions. However, if the soil is saline, the resonance amplitude gets reduced with increased salinity levels and exhibits moisture content independence and hence no frequency variation.

Keywords— Precision agriculture, Chipless, FDR, UHF, RFID, Soil Salinity, Folded monopole.

I. INTRODUCTION

Precision agriculture (PA) or precision farming is a farm management approach that makes the practice of farming more controlled and precise. This approach is essentially based on information technology and data collection from different sources using sensors, drones, autonomous vehicles, robotics, variable rate applications and so on [1-2]. It uses an extensive range of sensing technologies for site specific crop management where it deals with factors like soil sensing, irrigation control, yield prediction and mapping [3]. Radio Frequency Identification (RFID) is a wireless data collection technology that uses electromagnetic waves to identify and track an object. This automatic identification technique uses a tag and a reader to communicate data. By exploiting sensor equipped tags, RFID technology can keep track of surrounding environment as well. Passive chip-based RFID tags can cost as low as 7-15 US cents whereas the price of the chipless versions may go even lower with a cost about less than a cent [4-5]. Chipless RFID sensors offer lower fabrication cost and long-term measurement ability and they have a simple, compact and printable structure. These added advantages made the chipless RFID sensors an optimum choice for sensor deployment in a mass scale.

Measurement of soil moisture and salinity contents is a key component of PA based crop management. Information on the status of soil moisture contents enable highly efficient irrigation scheduling which optimizes the water usage in agricultural lands [6]. Soil salinity is an important parameter which has a direct impact on crop production. Presence of salt in soil restraunts the rate and amount of water that the plant roots can absorb from soil. Thus, soil salinity level controls the osmosis process of water. A highly saline soil can cause dehydration of plants by interfering with their nitrogen uptake and hence it can be quite toxic to the plants and perturb the crop production [7]. Therefore, it is of extreme importance to use a low-cost pervasive soil moisture and salinity sensing system in precision farming. There have been several different approaches adopted so far to provide soil moisture and salinity sensing for commercial applications. However, most of the commercial sensors and the ones that are reported in literature are either quite complex in terms of system and structure or quite costly. For conducting an accurate measurement, such sensors require a high amount of soil solution as well [6]. An FDR (frequency domain reflectometry) based sensor is reported in [8] which has a visually similar structure to the sensor proposed in this paper. However, the sensor is limited in its ability as it is not frequency specific and can provide selective determination of soil moisture only. It also brings complexity into the sensor structure by incorporating different layers of materials [8].

This paper proposes an inexpensive passive chipless RFID sensor that can monitor the salinity and moisture levels in soil. Although chipless, this sensor is designed at the UHF RFID band so that it can be easily tweaked to form a chip-based sensor if required. The novelty of this sensor lies in the fact that along with moisture and salinity sensing, it provides a provision for incorporating identifiability using a RFID chip. The designed sensor uses a simple (a single layer copper sheet) and compact U-shaped folded monopole. A theoretical model of the saline soil is formed here for simulating the proposed sensor in different saline environments. The convergence of experimental results with the simulated analysis shows that the sensor provides a novel and low-cost soil moisture and salinity content detection scheme, despite its minimized structural complexity.

II. THEORY AND SENSOR DESIGN

The proposed sensor is designed and analyzed using the commercial electromagnetic solver CST microwave studio. A soil model with different moisture and salinity contents is formed in the solver software and the designed sensor is
inserted into that model to analyze its performance at various soil conditions. The dielectric mixing model by Dobson [9] is utilized here to form the soil model.

A. Theory and Formation of Soil Model

Dobson’s model [9] relates the volumetric moisture content, \( m_v \), of a soil water mixture and its dielectric constant over a certain frequency range of microwave band. This semi-empirical model is modified by using the Stogryn formulation to provide the real and imaginary parts of the saline soil solution [10] depicted in equations (1) and (2) respectively:

\[
\varepsilon_{\text{SW}}' = \varepsilon_{\text{SW}0} + \frac{\varepsilon_{\text{SW0}} - \varepsilon_{\text{SW}00}}{1 - (2\pi f \tau_{\text{SW}})^2} \\
\varepsilon_{\text{SW}}'' = \frac{2\pi f \tau_{\text{SW}} (\varepsilon_{\text{SW0}} - \varepsilon_{\text{SW}00})}{1 - (2\pi f \tau_{\text{SW}})^2} + \frac{\sigma_I}{2\pi f \varepsilon_0}
\]

Here, \( f \) is the frequency in hertz, \( \varepsilon_0 \) is the free space permittivity given by \( 8.854 \times 10^{-12} \text{ Fm}^{-1} \), \( \varepsilon_{\text{SW}0} \) is the static dielectric constant of water and \( \varepsilon_{\text{SW}00} \) is the high frequency limit of \( \varepsilon_{\text{SW}}' \). Here, \( \tau_{\text{SW}} \) and \( \sigma_I \) represent the relaxation time and the ionic conductivity of the salt (NaCl) solution [7]. To obtain a soil model for simulation, the above equations are used to estimate the dielectric constant of sand and sea water mixture at 1.5 GHz. The real and imaginary dielectric constants of the mixture for moisture content \( (m_v<0.4) \) and salinity \( (S<100^\circ/\text{oo}) \) are depicted in fig. 1 and 2 respectively.

![Fig. 1. Effect of soil salinity variation on real dielectric constant for different moisture contents [10]](image1)

![Fig. 2. Effect of soil salinity variation on imaginary dielectric constant for different moisture contents [10]](image2)

Salinity and the concentrations of individual chemical constituents in sea water are expressed in parts per thousand for which the symbol \( ^\circ/\text{oo} \) is used in the depicted figures. The theoretically obtained real and imaginary dielectric constants of sandy soil (at 1.5 GHz) are utilized to create the soil simulation models with different moisture and salinity contents. To obtain the loss tangent, \( \tan\delta \), the following formula is used:

\[
\tan\delta = \frac{\varepsilon''}{\varepsilon'}
\]

B. Sensor Design

Fig. 3 shows the proposed U-shaped folded monopole-based sensor along with its dimensions. This sensor is designed by using a double-sided copper coating on Taconic TLX-9 with substrate permittivity, \( \varepsilon_r = 2.5 \) and loss tangent, \( \delta = 0.0019 \). It has a size of \( 90 \times 40 \text{ mm}^2 \) and the width of each of its arms is 10 mm while the thickness of both the copper layers is 35 \( \mu \text{m} \). The designed sensor operates at around 990 MHz at free space with a second harmonic at around 2 GHz. In order to make it operable in the UHF RFID band, the folded monopole resonator is designed to operate at 960 MHz when inserted into dry soil. This eventually shifts its free space resonance at 990 MHz.

III. SIMULATED RESULTS

Fig. 4 shows the simulation setup for the designed sensor to extract soil moisture and salinity variation from the formulated soil model. Here, the folded monopole resonator is penetrated into the soil model with varied moisture and salinity contents and its S-parameter (return loss) is determined by using CST microwave studio.

![Fig. 4. Simulation Setup for soil moisture and salinity variation analysis](image3)
Fig. 5 shows the simulated soil moisture content variation at zero salinity. It can be observed that the resonator operates at 960 MHz with a s-parameter amplitude of 2.7 dB at the dry soil condition. As the moisture content increases, the resonance frequency encounters a left shift towards the lower frequency values. The higher moisture contents result in an increase in the s-parameter amplitude levels in comparison to the dry soil response.

Fig. 6 shows the simulated sensor response for salinity variation at different fixed soil moisture levels. It can be observed from fig. 6 (a) that for a fixed volumetric moisture content of 0.1, the sensor operates at a band of 890-930 MHz. As the salinity level increases from 20 to 100 parts per thousand, the resonance amplitude keeps reducing which gets saturated at higher salinity values. A similar phenomenon is also observed for the salinity variation cases at other fixed moisture levels (m_v = 0.2 to 0.4) as depicted in fig. 6(b)-(d) respectively. In all these cases, the response for the lower salinity content (20 parts per thousand) exhibit a comparatively sharper notch which tends to get flattened with reduced amplitude at higher salinity. However, these amplitude levels remain quite distinct from each other, allowing the determination of different salinity contents. As the moisture content increases, it slightly shifts the sensing zone of the resonator.

IV. EXPERIMENTAL RESULTS

A prototype of the proposed sensor is fabricated, and its experimental analysis is carried out by using the Anritsu Vector Network Analyzer (VNA). Fig. 7 shows the designed prototype and its measured free space response which validates the simulated results. Fig. 8 exhibits the experimental setup of the sensing resonator where it is penetrated into soil and connected to the VNA for measurements.

Fig. 9 shows the measured sensor response due to moisture variation of soil while the salinity level is zero. It can be observed that the added water level incurs a resonance shift of the sensor towards lower frequencies which absolutely complies with the simulated results. As the water level increases, the sensor response goes beyond the UHF RFID band. However, interestingly, as salinity content is added, the response seems to get fixed at a certain frequency range [3]. The designed resonator is optimized to operate at 905 MHz during saline condition.
Hence, fig. 10 exhibits distinctive amplitude levels for different saline molarity and therefore, bestows the fact that the designed resonator can be used as a soil salinity sensor. To execute this experiment, 0.5844g of NaCl was added in 100mL water to create a 0.1 M saline solution. To enhance the molarity levels, different multiples of 0.5844 g NaCl was added to 100 ml water. This experiment was carried out for several water levels including 200 ml-400 ml and every time a similar response to the one depicted in fig. 10 was observed. This signifies that the salinity content response of the designed sensor is quite robust and moisture level independent. As it is observed, in terms of moisture level independence, the obtained experimental results are slightly different from the simulated results as the simulated ones showed frequency shift even at saline conditions. Also, for the moisture variation, the simulated results show a consistent variation of resonance whereas for measured results, the deviation between the dry and 40 ml water levels are quite negligible. This is because, when the 40 ml water is poured into the soil container, it does not spread over the entire soil sample to instigate a significant change. As the water level increases, the variation becomes more prominent.

V. CONCLUSION

This paper has focused on the design and analysis of a low-cost novel chipless RFID based soil moisture and salinity sensor based on a simple folded monopole resonator. Here, a soil simulation model in terms of different dielectric constants is formed by using a theoretical dielectric mixing model in order to provide various soil moisture and salinity contents. To obtain the simulated moisture and salinity variation, the proposed sensor is analyzed by using the formed model. A fabricated prototype of the sensor is experimentally analyzed to validate its operability and robustness. This ultra-simple structure-based sensor can distinguish between different salinity levels in soil. The future work will incorporate an RFID chip into the designed sensor to add identifiability in the sensing scheme. The wireless interrogation of the sensor using a RFID reader will also be investigated in future. The proposed sensor prototype offers a remarkable solution towards the commercialization of a low-cost soil moisture and salinity sensor with minimal design complexity.

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