Real-Time Wireless Moisture Sensing in Concrete Using Interdigitated Stick-on Sensors

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Abstract: The analyses, design, and performance of an interdigitated moisture sensor are presented. The analytical results clearly delineate the scope of the design in terms of the expected electric field penetration depth and interelectrode capacitance when the sensor is placed on top of a Material Under Test (MUT) for a simple two electrode sensor. A multielectrode circular sensor was fabricated, instrumented, and used to measure concrete moisture content. Real-time moisture measurement results in both fresh concrete (when curing) and dry concrete (when moisture intrusion is occurring) are presented in a wireless system level measurement scenario where the measured results are relayed to a distant receiver using a wireless transmitter. Copyright © 2015 IFSA Publishing, S. L.

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1. Introduction

Real-time moisture measurement of materials is very important in many fields of applications. For example, the presence of moisture in reinforced concrete structures facilitates the penetration of chlorides through concrete and leads to corrosion of the steel reinforcement. Over time, this leads to structural degradation and potentially failure of the structural system. Having a reliable method to measure the moisture in concrete over long periods of time could aid in determining the probability of corrosion in a structure. Regular moisture measurements of soil lead to efficient irrigation and not over or under watering of agricultural land. Soil moisture measurement data can also be a good predictor of future unforeseen forest fire occurrence. Houses with extreme moisture presence can be prone to termite intrusion and so on.

There are many choices when deciding to design and use a sensor to measure moisture in materials [1-13]. Near-field low frequency electrostatic type sensors that rely on capacitive probing are quite easy to design and use. Among them one of the most interesting one is the interdigitated sensor [6-13] because of its conformal geometry. Other applications of interdigitated sensors that have been reported include those for application in chemical sensing [14, 15], gas detection [16], resin curing [17] etc. In one of our earlier works [9] we have designed and developed interdigitated sensors that can detect insulation degradation in unshielded power cables. Subsequently
we also introduced interdigitated sensors [10] for moisture content measurement in concrete.

This paper presents a more in-depth analytical investigation of an interdigitated sensor followed by the experimental fabrication, testing, system level instrumentation, and real-time wireless monitoring of concrete moisture data as function time. Unlike our previous works where we were focused on the proof of concept, this paper demonstrates how such sensors can be efficiently and effectively implemented in a real world application of wireless concrete moisture sensing.

The paper is organized as follows. First, an analytical study of a unit cell of an interdigitated capacitor is presented that elucidates the expected electric field penetration depth and interelectrode capacitance as function of the sensor’s geometrical parameters. The analytical results are compared with simulation results obtained from Ansys Maxwel 3D solver. Second, to perform real-time wireless moisture measurement in concrete an interdigitated sensor and associated circuitry are designed for easy interfacing with two Commercial Off-The-Shelf (COTS) wireless transceivers. Third, experimental real-time wireless moisture content measurement results are presented as a freshly made concrete specimen cures over a period of one week. Fourth, Real-time wireless moisture content measurement results as function of moisture intrusion in a specimen of dry concrete are presented. Finally, a battery operated wireless moisture sensor is shown in a system level operation for a concrete specimen where moisture increases in the specimen.

2. Analytical Model and Results

An interdigitated sensor consists of two or more planar electrodes that come in contact with the Material Under Test (MUT) [9]. A low frequency sinusoidal voltage signal, $V_D$ is applied to the driving electrode which creates fringing electric field lines in the MUT. The fringing fields cause a voltage ($V_i$) at the sensing electrode which is picked up after passing through a voltage follower amplifier that contains a feedback capacitor, $C_F$. A quantity called the interelectrode capacitance, $C_{DS}$ is then found as $C_{DS} = (V_S/V_D)C_F$. If the moisture content and hence the dielectric constant in concrete varies the fringing fields also vary which then change $C_{DS}$. Thus the change in $C_{DS}$ is the basis of the moisture content measurement in the sample.

The geometry of a unit cell of an interdigitated sensor is shown in Fig. 1. It consists of a driving and a sensing electrode printed on a dielectric substrate with thickness $h_e$ and dielectric constant $\varepsilon_r$. The width of each electrode is $w$ and their separation distance is $a$. The conducting electrodes are each $h_e$ thick. This thickness is very small and thus $h_e << h_i$. The driving and sensing electrodes are at potentials $V_0$ and 0, respectively. The sensor unit cell is immersed in a dielectric medium where it creates electric flux lines as illustrated in Fig. 1.

For simplicity of analysis, a guard electrode was not considered in the analysis. A guard electrode at ground potential can be added in an actual sensor which can provide protection from undesired Electromagnetic Interference (EMI). The two-dimensional electric field distribution for the proposed scheme can be solved using conformal mapping techniques [18]. As the flux lines are elliptical and the equipotential lines are hyperbolic, the best way to attack this problem is to use inverse cosine transforms. Similar types of approaches were adopted in [18]. As it is a solution of the two-dimensional electric field, the lengths of the electrodes are taken as infinitely long. The electric fluxes start at the driving electrode, penetrate the material under test (MUT) and then end at the sensing electrode. The following assumptions were made in the analysis.

The thickness of the MUT on either side of the sensor surface, $h_m$, must be greater than the field penetration depth $T$, corresponding to the maximum vertical displacement of field lines in the $y$ direction, i.e., $h_m > T$.

1. The substrate thickness is negligible compared to the height of the MUT i.e., $h_e \ll h_m$, so that the flux distribution is not perturbed by the substrate material.

2. The electrode height $h_e$ is negligible compared to the height of the MUT i.e., $h_e \ll h_m$. As a result, the direct fluxes between the two electrodes are also negligible.

Applying conformal mapping techniques and satisfying the boundary conditions it can be shown [19] that the electric field penetration depth, $T$ is given by

$$T = \frac{a}{2} \sinh \left[ \cosh^{-1} \left( 1 + \frac{2w}{a} \right) \right]$$  \hspace{1cm} (1)

Using hyperbolic trigonometry,

$$T = \frac{a}{2} \sqrt{\left( 1 + \frac{2w}{a} \right)^2 - 1}.$$  \hspace{1cm} (2)
Since $b - a = 2w$

$$T = \frac{a}{2} \sqrt{\left(\frac{b}{a}\right)^2 - 1}$$  \hspace{1cm} (3)

From (2) and (3), $T$ can be calculated as function of $w$ and $a$.

The dependency of the field penetration depth, $T$ on $w$ and $a$ is shown in Fig. 2 (a). It is clear that $T$ increases with an increase in $w/a$. In Fig. 2(b), we plot $T$ versus $w$ for the distance between the two electrodes ($a$) varying from 0.05 mm to 5 mm. The width of each electrode, $w$ affects $T$ more than the interelectrode separation $a$ does. From the figure, for $w=2$ mm $T$ increases from 2.5 to 3.7 mm as $a$ increases from 1 mm to 5 mm. In contrast, $T$ doubles as $w$ doubles.

![Fig. 2. Calculated electric field penetration depth, $T$.](image)

Also from (2) (b) for $a$ less than 0.5, nearly all the curves can be approximated by the relation $w=T$. But as $a$ increases $w$ diverges from this relationship. For example, for $a=5$ mm and $T=5$ mm we need $w=4$ mm. For $T=2$ mm and $a=5$ mm, the $w$ versus $T$ curve is nonlinear. When $\frac{w}{a} > 1$, (2) can be approximated as $T \approx \frac{a}{2} + w$ which is a straight line while when $\frac{w}{a} \gg 1$, (2) can be approximated as $T = w$.

Using a similar procedure the electrostatic capacitance can also be calculated as outlined in [19]

$$C = \frac{2 \epsilon \epsilon_0}{\pi} \ln \left[ \frac{b}{a} + \sqrt{\left(\frac{b}{a}\right)^2 - 1} \right]$$  \hspace{1cm} (4)

The variation of the total capacitance $C$ between the driving and sensing electrodes with respect to $w$ from 1 mm to 100 mm and $a$ from 1 mm to 10 mm is plotted in Fig. 3.

Fig. 3 shows the surface plot of per unit length capacitance without considering the dielectric constant of the material (or considering only air) $C$ with respect to electrode width $w$ and the distance between the two electrodes $a$. Capacitance decreases with increasing $a$ and increases with increasing $w$. Fig. 3(b) further clarifies Fig. 3(a).

![Fig. 3. Capacitance vs. $w$ and $a$.](image)

To better understand our analytical results and compare, we also modeled and simulated a unit cell interdigitated capacitor using Ansys Maxwell 3D. The driving electrode was set to 10 V and the sensing electrode was set to 0 V. The heights of the electrodes...
were set to 0.5 mm. The relative permittivity, $\varepsilon_r$, of the material under test considered for the simulations was 2.2 (Duroid 5880).

A comparison between analytical solution (4) and Maxwell simulation is summarized in Table 1. As apparent, the percentage of error in the analytical simplified model results compared to the simulation results decreases from 14% to 6% as $\frac{w}{a}$ increases from 1 to 20. If both $w$ and $a$ are same such as $w = a = 1, 2, 5$ and 10 mm the error is almost constant which is close to 14%. Therefore, Table 1 confirms that when $\frac{w}{a}$ increases, the discrepancy between the analytical solution and the simulation result decreases.

Table 1. Comparison between analytical solution and simulation results of capacitance from Ansys Maxwell 2D for different $\frac{w}{a}$.

<table>
<thead>
<tr>
<th>$w$ (mm)</th>
<th>$a$ (mm)</th>
<th>$\frac{w}{a}$</th>
<th>Analytical 2D</th>
<th>Maxwell 2D</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>21.86</td>
<td>25.45</td>
<td>14%</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>28.43</td>
<td>32.3</td>
<td>12%</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>5</td>
<td>38.31</td>
<td>42.21</td>
<td>9%</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>10</td>
<td>46.34</td>
<td>50.13</td>
<td>7%</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>20</td>
<td>54.64</td>
<td>58.58</td>
<td>6%</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>1</td>
<td>21.85</td>
<td>25.51</td>
<td>14%</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1</td>
<td>21.85</td>
<td>25.67</td>
<td>15%</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1</td>
<td>21.85</td>
<td>25.34</td>
<td>14%</td>
</tr>
</tbody>
</table>

It is clear that larger electrode size and small separation are key to achieve higher capacitance and hence better measurement quality. Similarly, for a given separation ($a$), larger electrode size will allow strong field penetration depth. However, from a practical fabrication and implementation point of view these are not always desirable. Thus design optimization is often necessary. Interestingly however, the simulation results always provide higher capacitance then the analytical thus the analytical results should be considered as conservative first order values. This means that the actual sensitivity should be better.

3. Design and Implementation of an Interdigitated Moisture Sensor

The above analytical and simulation results will guide us design practical interdigitated sensors for moisture content measurement of materials. As stated before change in moisture in a MUT means change in its dielectric constant. This change is reflected as a change in the sensor’s interelectrode capacitance. Hence once the sensor is instrumented with a proper circuitry a variable output voltage will appear at the sensor’s sensing electrode. For the purpose of this work we considered to monitor the moisture change in concrete both when concrete was curing from fresh condition as well as when there was water intrusion in concrete as function of time. A multielectrode sensor was designed following the analytical results as well as results from our previous works [9-10], [19-20]. Fig. 4 shows the geometry of the interdigitated sensor that was designed, fabricated, and tested. During practical usage, the top surface of the sensor will be brought in contact with the MUT. It has three types of electrodes, namely, driving electrodes, sensing electrodes, and guard electrodes. These electrodes were fabricated on a 3.2 mm thick Duroid 5880 substrate. There was a conducting layer on the backplane of the substrate which was connected to the ground. The electrode width, $w$ and the gap between the electrodes, $a$ were 1.5 mm and 2 mm respectively. The field penetration depth, $T$ is thus approximately 2 mm (Fig. 2 (b)). The inner diameter of the innermost sensing electrode was 6 mm.

There were twelve driving electrodes, ten sensing electrodes, and two guard electrodes. A 1-kHz, 10-V sinusoidal signal was applied to the driving electrodes. The amplitude of the signal was small enough to prevent the opamp from saturating. This also ensured a high enough output signal above the noise level. The sensing electrode is virtually grounded by an opamp in a voltage follower configuration, and the output voltage develops across a feedback capacitor $C_F$ of 100 pF. The output voltage when passed through a 10 µF DC blocking capacitor is measured as $V_F$. The opamp also isolates the sensor circuit from the measuring devices and hence prevents loading effect on the sensor. The backplane and the guard electrodes (which are usually kept at ground potential) remove any unwanted influence from external fields. The backplane also restricts field leakage in the backward direction.

4. Wireless Implementation

To monitor and record real-time changes in moisture content in a material wireless transmission of measured data was attempted. Since the output of the
sensor is a voltage a higher output voltage value would indicate higher moisture while a lower output voltage value would indicate lower moisture.

Two 900 MHz wireless transceivers and a built-in software interface were purchased from a company called Embedrf (Fig. 5). One of these transceivers was used as the transmitter and was connected to the sensor’s output port. The second transceiver was used as the receiver while remaining connected to a computer that recorded the data. A block diagram shown in Fig. 6 illustrates these steps.

The first challenge we faced was that the sensor’s output voltage was a time varying sinusoidal signal whereas the Embedrf wireless transmitter could only handle DC outputs with amplitude < 3 V. To overcome this barrier one of the sensor’s existing opamps was leveraged to design a precision rectifier circuit that could convert the time varying measured output to DC. The AD708 omamp selected for the interdigitated sensor (it is used as a voltage follower) was a dual opmap of which the second one was used to design and fabricate the precision rectifier.

Spice simulations were performed to analyze the performance of the precision rectifier. The circuit diagram of the precision rectifier is shown in Fig. 7(a) while the rectified output is shown in Fig. 7(b). As can be seen the red input signal has been converted into a blue DC signal. A small 10 μF polar capacitor was used to reduce the ripple in the output. As observed, there is almost no voltage drop in the output dc voltage (blue curve) due to the diode forward voltage. Before integrating the sensor, the voltage follower and the precision rectifier on a single Printed Circuit Board (PCB), a starter prototype of the sensor was built. The circuit components were assembled on a breadboard and connected to the sensor output. The EmbedRF transceiver has a limitation that it becomes saturated if its input voltage is > 3 V. To prevent this, a 1:1 voltage divider circuit was used. This voltage divider reduced the DC amplitude by 50 %.

Preliminary tests were performed on a number of everyday materials. The sensor with its sensor side pointing down was placed on the test specimens. The backplane was on the top. To ensure proper contact between the sensor electrodes and the sample, a block of concrete was used as weight on top of the backplane. The sensor was driven using a 10 V 1 kHz AC signal. To drive the opamps a DC signal generator was used. The Embedrf wireless device was connected to the DC output of the sensor. The same DC output was also connected to a DC voltmeter. To prevent damage of the Embedrf transceiver from Electro-Static Discharge (ESD), an ESD safe mat and an ESD...
wrist strap were used while handling the Embedrf transceiver. Sensor output voltage (DC) data were directly recorded from the voltmeter connected to the output. The wireless output voltages received by the Embedrf wireless receiver placed approximately 20 ft away from the transmitter were also recorded. As an initial test several different types of materials were tested as listed in Table 2. It is clear that a high output voltage is correlated with high moisture content, e.g. beef stake (high moisture) vs dry wood (low moisture). Also note that direct measurement data and wireless readouts are nearly identical.

Fig. 8 shows the front and backsides of the final sensor prototype. The voltage follower and the precision rectifier were fabricated on the back side of the sensor. This ensured uniform interfacing of sensor front side with the material under test and also helped avoid damage of the circuit components. The same sensor was also designed to work as an antenna for sensor data communication. However, because the Embedrf wireless transceiver had a built-in PCB antenna the designed antenna was not used.

### Table 2. Sensor response to different materials.

<table>
<thead>
<tr>
<th>Material Under Test (MUT)</th>
<th>Sensor output; direct measurement (V)</th>
<th>Sensor output; wireless measurement (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A piece of dry wood</td>
<td>0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>Flour dough</td>
<td>1.68</td>
<td>1.66</td>
</tr>
<tr>
<td>A piece of beef Steak</td>
<td>2.07</td>
<td>2.1</td>
</tr>
<tr>
<td>A slice of white bread (regular)</td>
<td>2.07</td>
<td>2.15</td>
</tr>
<tr>
<td>FR4 PCB</td>
<td>0.40</td>
<td>0.39</td>
</tr>
</tbody>
</table>

5. Wireless Moisture Sensing of Fresh Concrete During Curing

The sensor shown in Fig. 8 was used in combination with wireless transceivers to conduct all subsequent measurements. Real-time moisture measurements were done on a concrete specimen that was recently poured and had significant moisture in it. A freshly made 6 inch square and 1 inch thick concrete block was used as the material under test. The experiment started within 6 hours after the concrete was mixed. Fig. 9 shows the measurement setup. Fig. 10 shows the wireless sensor voltage readout as a function of time. It was observed that the voltage did not change significantly even after 150 hours (more than 6 days) likely because the specimen was kept indoors in an air conditioned lab. To save time we decided to accelerate the concrete curing process by circulating warm air from a fan heater on the concrete. The accelerated drying regions are encircled in Fig. 10. It was found that when warm air was blown, the sensor output started to decrease rapidly, but when warm air flow was slow or stopped, the voltage again rose.

![Fig. 9. Wireless moisture content measurement of fresh concrete.](image)

![Fig. 10. Data recorded by wireless receiver, circles indicate accelerated drying by fan heater.](image)

The reason behind this behavior is that the region near the surface dried out quickly when warm air was blown. Since the sensor can sense moisture mostly within 2 mm from the surface, its output decreases when the heater fan was on. But when the air flow was stopped, the dried out section quickly absorbed moisture from the inside of the specimen and the sensor output increased. This tendency of sharp voltage drop and rise decreased after several cycles as seen from Fig. 10. This is most likely because of a reduction of the moisture in the specimen due to evaporation on the surface and the curing process. The weight of the concrete just before starting of the experiment was found to be 1180 gm. The voltage
measured at the beginning of the measurement was 1.58 V. At the end of the experiment the measured voltage was 0.21 V. The weight of the concrete was 1150 gm. The weight of the moisture that evaporated was 30 gm which was 2.6 % of the weight of the dry concrete.

6. Wireless Moisture Sensing of Dry Concrete While Moisture Intrusion is Occurring

Followed by the success of the real-time moisture measurement of a freshly mixed concrete specimen we decided to conduct a similar experiment on a dry concrete block in which water starts to intrude as function of time. An analogous scenario could be found in concrete or wood bridge piers after a storm or during high and low tides. The moisture content in the structural element will increase because of the rising waters.

In this experiment, water intrusion into dry concrete was measured over a period of time. The concrete under test was made 2 years ago and was considered completely dry. The length, width and height of the concrete sample was 6 inches by 6 inches by 4 inches. As seen in Fig. 11 (b), this concrete sample was submerged in water inside a container. The water height was 2 inches and thus it was covering 50 % of the specimen. Measured wireless sensor output data are plotted against time in Fig. 11 (a). It is observed that up to 11 hours there is no significant change in the output voltage. Beyond 12 hours, the voltage starts increasing. The initial voltage when concrete was dry was 0.25 V but after 20 hours of water absorption, the sensor output increased to 1.7 V.

7. Battery Operated Wireless Moisture Sensing of Dry Concrete While Moisture Intrusion is Occurring

Previously the experiment was performed using DC power from a signal generator. One of our goals was to operate the sensor without any large external DC power supply. So we performed the measurement with the sensor being supplied with 6 V DC from batteries. One 100 mAh 3 V battery was in series with one 11 mAh 3 volt battery to give +6 V output. Another identical setup was used to get -6 V dc output. The concrete block we used here was much smaller. The specimen was only 6 inch by 6 inch by 1 inch. Fig. 12 shows the experimental setup and Fig. 13 shows the water level. The concrete under test was placed on a thick base concrete and the water covered 50 % of the specimen. Thus only about 0.5 inch of concrete was above water.

Fig. 14 shows the measurement results. The concrete absorbs moisture and saturates very quickly, within 30 minutes. The zoomed version of the curve for the first two hours is also shown. This proves that when the concrete sample is thin water is absorbed far more quickly. The weight of the dry concrete just before the starting of the experiment was 1030 gm. The voltage measured at the beginning of the measurement was 0.19 volt. At the end of the experiment the measured voltage was 0.80 volt. The
weight of the concrete was 1080 gm. The weight of the moisture that was absorbed was 50 gm which was 4.8 % of the weight of the dry concrete.

There is a slight decreasing tendency of recorded voltage at the end. This might be due to the reason that the sample concrete used here was much smaller in both size and weight than the concrete used in the previous experiment. Another reason might be that the battery voltage decreased with time, so the peak voltage output for saturated concrete might have exceeded the battery voltage. This means peak output voltage follows battery voltage. If the battery voltage was fixed, the output should be fixed for saturated concrete. But due to decrease in battery voltage there was decrease in output.

8. Conclusion

The objectives of this work were to develop a simplified analytical formulation of interdigitated near-field sensing and to design, fabricate and test a sensor to measure moisture presence in materials. Furthermore, real-time moisture measurement results are relayed to a distant receiver under a wireless setting that shows the feasibility of such an approach. First, the fundamentals of interdigitated sensing are formulated and the design space is defined which clearly show the relationship between the electrode sizes and their spacing in determining the field penetration depth and the inter-electrode capacitance in the MUT. It was shown that for large electrode width to separation ratios the results obtained from our analytical solutions approached the results from Finite Element Electromagnetic (EM) field solvers. The proposed analysis can be used for the quick analysis and design of proximity interdigitated sensors.

Based on the analysis and from our prior experience with such sensors a sensor and its associated data processing circuitry such as a voltage follower plus a precision rectifier were built and tested. The sensor demonstrated consistent measurement capability in terms of predicting the presence of moisture in materials. Real-time Moisture measurement data conducted on a fresh concrete specimen for over a period of 2 weeks show that there is a significant drop in the sensor output voltage as the concrete cures (a factor of 8 change). Measurement for cases where moisture intrusion is occurring show that the effects are much faster; depending on concrete thickness the onset of moisture intrusion are measured in hours as opposed to days when fresh concrete is curing. Finally, battery operated wireless moisture sensors also show similar behavior except for the absolute values of the voltage readouts between different states (dry versus moist).

Acknowledgements

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