20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Diffused capacitance-based sensing for hydric control and watering optimization

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Abstract – **Soil moisture measurements are essential especially in the agricultural field, where it is crucial to guarantee that the optimal amount of water is provided to the cultivations. Most soil moisture measurement systems are local sensors; hence, a multitude of sensors must be distributed all over the field to obtain a comprehensive picture of the soil condition. Starting from these considerations, the present work addresses the feasibility of employing diffused sensing elements (in a wire-like configuration) for sensing soil moisture variations, based on capacitance measurements. To this purpose, for a preliminary validation of the proposed methodology, several experiments were carried out, thus identifying the suitable setup configurations and the potential of the method.**

I. INTRODUCTION

Measuring soil water content is essential especially for agricultural water management, where the optimization of the use of water resources is crucial and strategic for the long-term competitiveness of the agricultural industry [1]. Soil moisture content measurements may rely on different technologies. For example, a 1.4-GHz soil moisture sensor using microstrip transmission line (to be placed in the soil) and an electronic transceiver was presented in [2]; whereas, in [3], the feasibility of using inexpensive wireless nanotechnology based devices for the field measurement of soil temperature and moisture was studied. Also time-domain reflectometry (TDR) is widely used for monitoring soil moisture content [4, 5]; however, for traditional TDR probes, soil moisture measurement depends on the placement of the TDR probe in the sample. Capacitance sensors are widely used for soil water content: in these measurements, the soil moisture content is determined by measuring the capacitance between soil implanted electrodes [6]. However, typically, these are local sensors with a limited sensing volume; therefore, several sensors must be positioned along the area to be monitored. This is the case, for example, also of some well-known commercial devices (such as the Decagon 10HS and 5TE sensors) for which, however, there are still some limitations regarding, for example, the effect of the electrical conductivity of the soil [7]. A comprehensive review of the methods available for estimating soil moisture and its implications for water resource management can be found in [6]. Despite the large number of devices readily available on the market for measuring soil water content, this is not a trivial task. In fact, there are a number of aspects that must be taken into account and that still motivate much research effort. For example, the response of different water sensors (resorting to time-domain reflectometry, a time-domain transmission sensor, and capacitance measurements) for soil measurements and in particular the effect of bulk electrical conductivity has been addressed in [8].

Starting from these considerations, the present work addresses the feasibility of employing diffused, flexible sensing elements (in a wire-like configuration) for sensing soil moisture variations, based on capacitance measurements. In practical applications, such a sensing element (SE) configuration would allow following the desired path along the cultivation field. These wire-like capacitance sensors would estimate an 'average' capacitance value along the SE, that could be related to the moisture content variation of the monitored soil, and hence it would provide an alert that the conditions all along the SE have changed and need further consideration. The idea may recall the use of a TDR probe placed vertically, which measures the arithmetic mean of soil moisture for the whole sample [9]; however, differently from TDR, the proposed system is expected to employ more rugged and less expensive pieces of equipment. For soil moisture measurements on larger volumes, also a method resorting to elastic waves for measuring moisture content in agricultural soils was presented in [10, 11]; nevertheless, that system configuration is hardly adaptable for specific water-irrigation control purposes.

ISBN-14: 978-92-990073-2-7

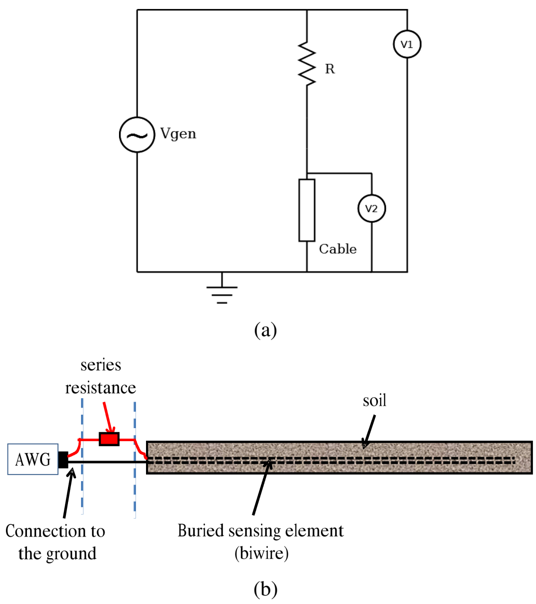


Fig. 1. Circuital schematization of the experimental setup (a); schematization of the apparatus (b).

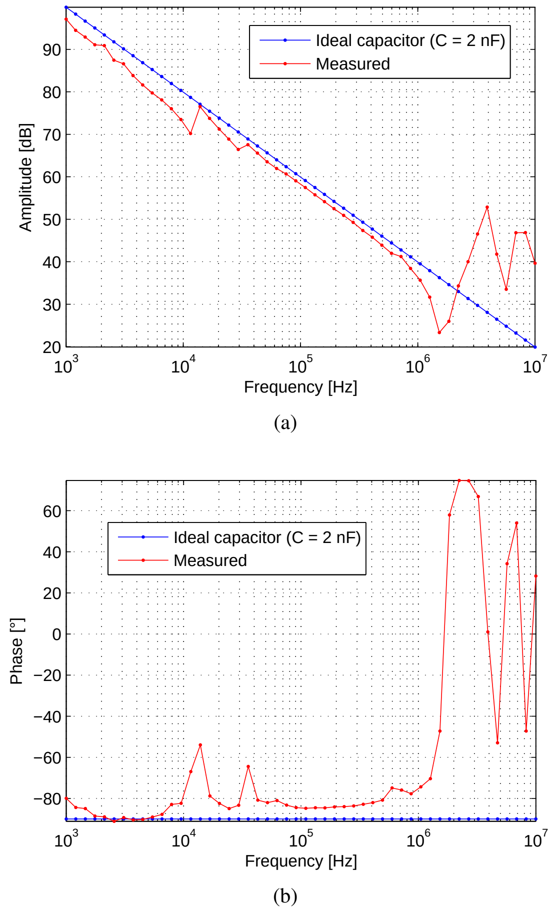


Fig. 2. Behavior of the electrical impedance of the buried SE in the 1 kHz-10 MHz frequency range: amplitude (a) and phase (b).

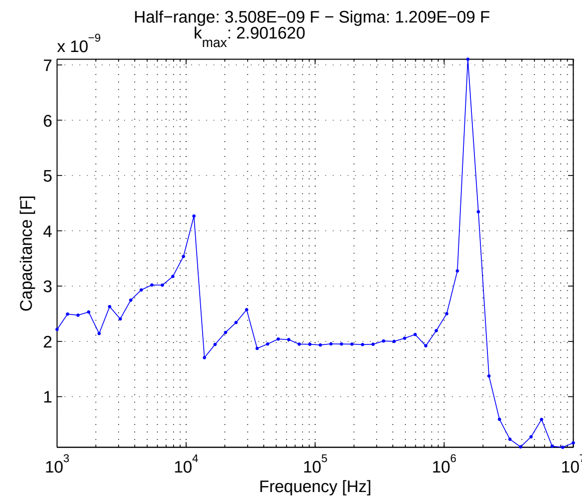


Fig. 3. Wide-band measurements: estimated capacitance as a function of frequency.

For a preliminary validation of the proposed system, several experiments were carried out, thus identifying the suitable setup configurations and the potential of the method. First, through electrical impedance measurements, it was verified the frequency range in which the sensing element exhibited capacitance-like behavior. Successively, 'pure' capacitance measurements were carried out. Finally, an experiment with varying soil moisture content was carried out.

II. EXPERIMENTAL SETUP

A circuital schematization of the experimental setup is shown in Fig. 1(a). An arbitrary waveform generator AWG (Agilent 33120A), with a 15 MHz bandwidth, was used to generate a sinusoidal signal and to propagate it along a resistance, and the sensing element connected in series. The used sensing element was a bi-wire, namely the 19 AWG (24x0.20 mm, 0.75 mm^2), in which the copper wires run parallel to each other and are separated by a PVC sheath (diameter 2.35 mm). From specifications, the capacitance between the two conductors is approximately 100 pF/meter, evaluated at 1 kHz. The length of the sensing element was approximately 15 m. A digital oscilloscope (Agilent 54603B), which has a 60 MHz bandwidth, was used to measure the voltage drop across the resistance and at the terminals of the resistance/SE series. To mimic the in-the-field condition, the SE was buried under red soil. Fig. 1(b) shows a sketch of the apparatus.

A. *Impedance measurements in the 1 kHz-10 MHz frequency range*

The preliminary step was to identify the frequency range in which the SE exhibited a predominantly-capacitive behavior. To this purpose, measurements were carried out to assess the variation of electrical impedance of the SE (buried under red soil) as a function of frequency.
Measurements were performed in the 1 kHz-10 MHz frequency range, with 50 measurement points. Results are shown in Fig. 2. This measurement was repeated after approximately 10 minutes; and the results (not reported here for the sake of brevity) showed a good repeatability over the considered frequency range.
It is worth noting that for the lowest (1 kHz-10 kHz) and for the highest (1 MHz-10 MHz) considered frequency ranges, measurements were severely affected by noise. In the former case, it was due to the high equivalent impedance of the sensing element (because the voltage signal on the sensing element and on the series resistance/sensing element are approximately equal). In the latter case, the signal amplitude on the sensing element was too low (i.e., equivalent impedance of the sensing element too little). It can also be noted that, in the lowest-frequency range, although the evaluation of the electrical impedance is clearly compromised by the amplitude of the test signal, the behavior of the SE is distinctly capacitance-like. On the other hand, in the highest considered frequency range, inductance-like behavior becomes more relevant: this can also be seen from the phase plot, which exhibits an abrupt change from -86° to +70°.

Fig. 3 shows the behavior of the estimated capacitance with frequency (the corresponding value of the standard deviation is also reported). It can be seen that, in the 50 kHz-500 kHz frequency range, the sensing element exhibits a more pronounced capacitance-like behavior and that the capacitance value can be considered constant. Therefore, this frequency range was selected for the subsequent narrow-band impedance measurements.

B. *Impedance measurements in the 50 kHz-500 kHz frequency range*

Fig. 4 shows the results of the electrical impedance measurements performed in a narrower frequency band, namely 50 kHz-500 kHz, and with the same number of acquisition points (i.e., 50). Fig. 5 shows the estimated capacitance, and also reports the estimated standard deviation (which has decreased by two orders of magnitude with respect to the previous case). Although, the corresponding uncertainty was still high (in the order of tens of picofarads) for the intended purposes of monitoring water content variations; this experiment was crucial to verify the predominantly capacitance-like behavior of the sensing element in the considered frequency range.

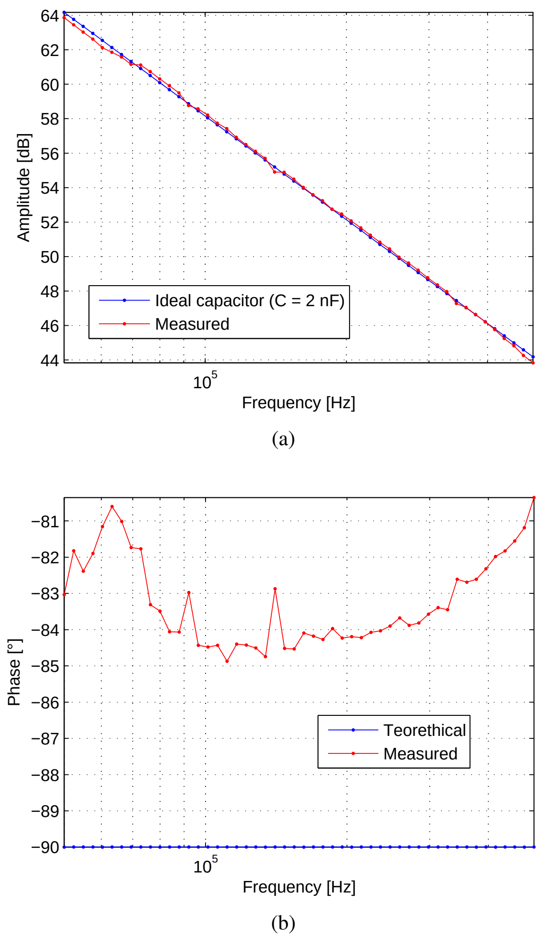


Fig. 4. Narrow-band impedance measurements (50 kHz-500 kHz) on the buried SE: amplitude (a) and phase (b).

C. *Validation of the capacitance measurements on the sensing element*

Based on the results of these preliminary experiments, capacitance measurements were performed selecting a frequency value of 100 kHz; Fig. 6 shows the results. It is worth pointing out that these measurements were carried out in stable (although non-controlled) conditions of the soil; in fact, they were conducted in a few minutes span, under good weather conditions. The results, however, show a maximum variation of 19.8 pF (hence, approximately ± 10 pF), which is still high considering that, based on separate experiments with wet soil (reported later in this paper), the capacitance variation associated to a change of moisture content is expected to be in the same order of magnitude.

These preliminary capacitance measurements evidenced some critical factors that affected the method, such as
1) interference at 50 Hz, generated by the electrical grid;
2) scarce reliability of the initial acquisitions, due to the warm-up phase of the instruments;

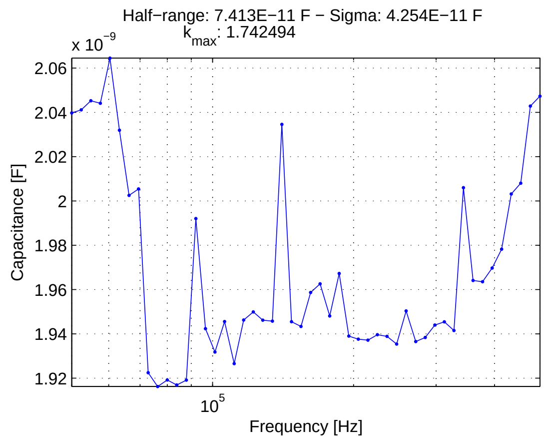


Fig. 5. Narrow-band measurements: estimated capacitance as a function of frequency.

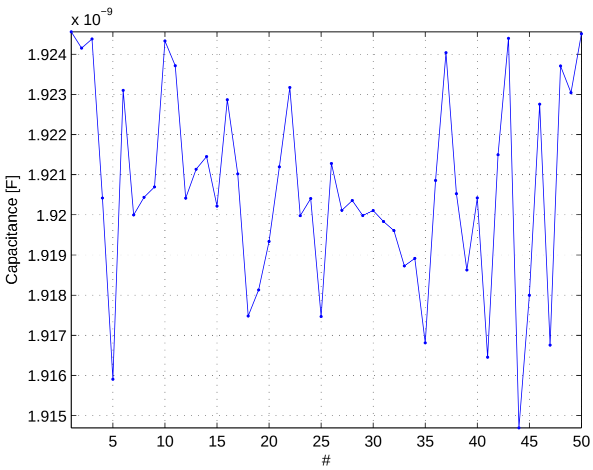


Fig. 6. Preliminary capacitance measurements carried out at 100 kHz (50 measurement points).

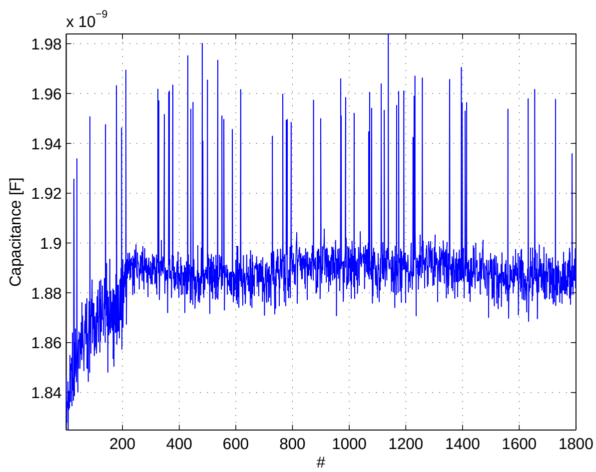


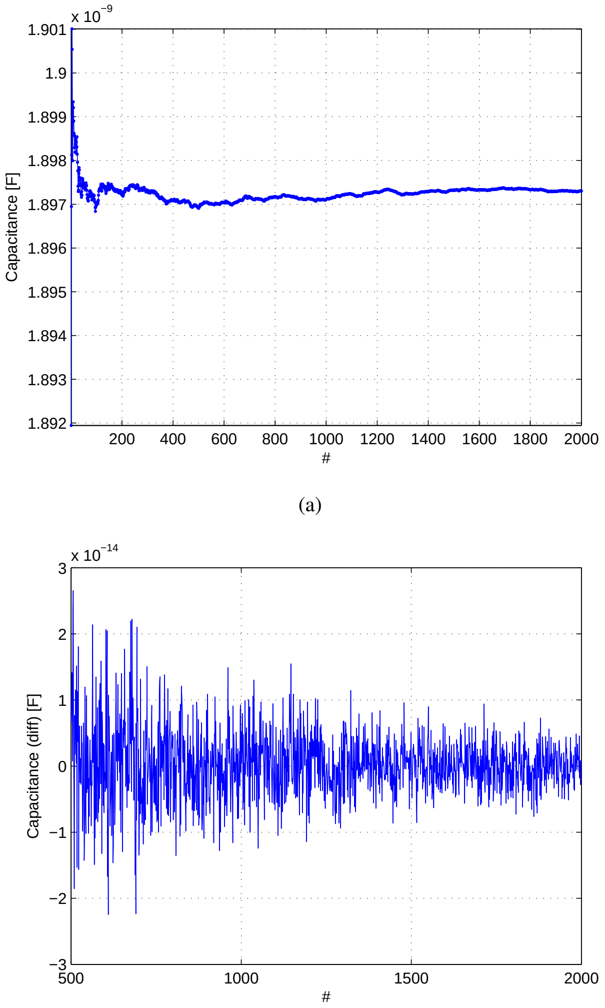
Fig. 7. Nocturnal measurements and evidenced outliers.

3) and, finally, non-ideal electrical connections.
To establish the limitations of the method, measurements were repeated during the night time; Fig. 7 shows the results. In the nocturnal run, the system evidenced the following limitations:
i) importance of the warm-up of the instrument;
ii) presence of big outliers (approximately 60 pF above the value considered as the 'actual' value);
iii) variance still high for the intended purposes.
Based on these preliminary results, in the successive measurements, the following strategies were adopted:
a) increasing the peak-to-peak amplitude of the sinusoidal signal up to 20 V;
b) the measurement instruments (both the oscilloscope and the waveform generator) were set-up at the beginning of the experiment and the settings were not changed until the end of the measurement run;
c) the sweep-time of the oscilloscope was set equal to the period of the signal, thus acquiring exactly one period for each measurement;
d) acquisitions were carried out in a continuous run-modality (i.e., without interrupting the sweep after each step).
This strategy provided excellent repeatability and, additionally, there was no outlier, as can be seen from the results reported below. Furthermore, to readily follow the variation of the capacitance and therefore of the moisture content profile in real time, averages were removed: this also allowed to perform measurements more quickly. Fig. 8 shows the results. The first 200 acquisitions exhibit a variation of the order of ± 10 pF, which rapidly reaches a 'steady' state, decreasing to few fF. The warm-up problem is not overcome; however, it can be dealt with simply by excluding a number of measurements at the beginning of each acquisition.

III. MEASUREMENTS WITH MOISTURE CONTENT VARIATIONS

Finally, to verify the response of the system in presence of variations of moisture content, the following experiment was carried out. To mimic the effect of the presence of water, a portion of the SE was unburied: approximately 60 cm, at a distance of approximately 5 m from the beginning of the SE. In correspondence of this portion of the SE, a water tap was opened and water was poured on the unburied portion of SE, eventually surrounding all the 60 cm-portion. Fig. 9 shows a schematization of the setup.

Fig. 10 shows the measured capacitance as a function of time (the first 300 acquisitions, related to the warm-up phase, were removed). The dashed green lines in correspondence of the discontinuities indicate the transition between two consecutive measurement runs (only a few minutes passed between two consecutive runs); whereas the red lines indicate two relevant 'events': opening and



(a)

(b)

Fig. 8. First 2000 acquisitions obtained with the validated method (a) and difference between two consecutive acquisitions in the steady-state (b).

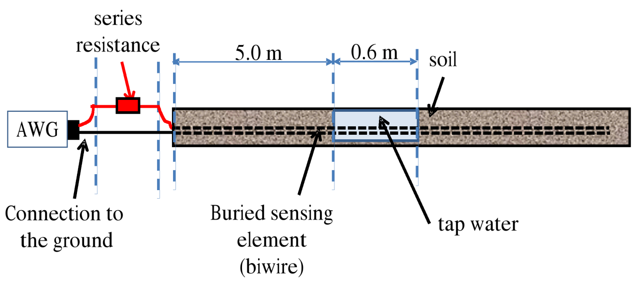


Fig. 9. Experimental setup for the experiment (not to scale).

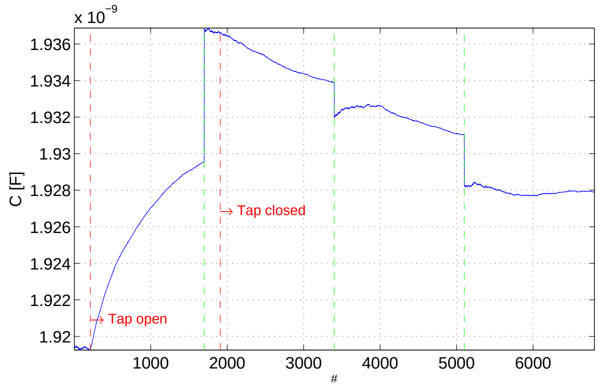


Fig. 10. Capacitance measurements carried out with varying water content conditions.

closing of the tap. It can be seen that, right after the tap was opened, the value of the measured capacitance progressively rose. Successively, after closing the tap, the capacitance value began to decrease as a result of the fact that it was progressively absorbed by the surrounding soil.

IV. CONCLUSIONS

In this paper, the feasibility of a soil moisture measurement method employing a low-cost distributed sensing element was preliminary validated. The proposed method exploits diffused capacitance measurement for sensing soil moisture content variations. The preliminary results demonstrate that the proposed system can sense a variation of the overall moisture content. In practical applications, the system may be used to generate an alert when the sensed moisture content variation exceeds pre-established ranges and an intervention is required. Additional in-the-field experiments will be carried out to further investigate the potential and limitations of the system.

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