Soil Moisture Scatter Radio Networking with Low Power

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A low-cost (6 Euro per sensor), low-power (in the order of 200 \( \mu W \) per sensor), with high communication range (in the order of 250 meter), scatter radio sensor network is presented, for soil moisture monitoring at multiple locations. The proposed network utilizes analog frequency modulation (FM) in a bistatic network architecture (i.e., the emitter and reader are not co-located), while the sensors operate simultaneously, using frequency division multiple access (FDMA). In contrast to prior art, this work utilizes an ultra-low cost software-defined radio reader, offers custom microstrip capacitive sensing with simple calibration, as well as modulation pulses for each scatter radio sensor with 50% duty cycle; the latter is necessary for scalable network designs. Overall root mean squared error (RMSE) below 1% is observed, even for ranges of 250 m. This is another small (but concrete) step for the adoption of scatter radio technology as a key enabling technology for scalable, large-scale, low-power and cost environmental sensor networking.

Index Terms—Scatter radio, sensor networks, soil moisture.

I. INTRODUCTION

MODERN agriculture applications necessitate cheap, effective, low-maintenance and low-cost wireless telemetry for various environmental parameters [1], such as environmental humidity, soil moisture, barometric pressure and temperature [2]–[5]. Continuous and dense environmental monitoring is critical for optimal crop and water management techniques and thus, wireless sensor network (WSN) technologies for microclimate monitoring in extended areas, are indispensable within this topic [1]. One important environmental variable that needs careful monitoring, especially in agriculture and water management applications, is percentage soil moisture (%SM). Prior art has offered novel soil moisture capacitive sensors integrated with discrete wireless radio module [6], [7] or discrete processing chip [8], including ink-jet fabrication designs.

Conventional WSNs consist of a network of nodes (possibly in a mesh architecture), transferring monitored environmental data to a base station. Each node typically employs a Marconi-type radio, controlled by a microcontroller unit (MCU) and the sensors. However, large-scale deployments of conventional WSN technology are uncommon, due to power consumption, installation and maintenance cost. Work in [9] is one rare case of large-scale, outdoor demonstration, with packaging/long-term deployment cost per wireless sensor in the order of 50 Euro.

In order to address power consumption and cost per sensor constraints, scatter radio has recently attracted interest for wireless sensing development (Fig. 1); using scatter radio, the front end of each sensor is simplified to a reflector that modulates information on the sensor’s antenna-load reflection coefficient; in scatter radio, communication is performed by means of reflection, where signal conditioning such as filtering, mixing or amplification at the sensor/tag are typically avoided; in that way, low power consumption is needed, offering opportunities for battery-less operation [10], [11], e.g., each sensor can be powered using ambient radio frequency (RF) energy with appropriate rectifiers (e.g., [12]–[14]) or using multiple kinds of ambient energy sources, such as RF and solar energy, simultaneously (e.g., [15]). Sensor designs with scatter radio typically exploit variations of sensor’s antenna properties [16], based on the environmental parameter under monitoring, such as the (mechanical) shape (e.g., [17]) or the dielectric constant (e.g., [18]); chip-less designs typically include appropriately-designed antenna loads.

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with delay lines (e.g., work in [19] and references therein); another way to construct scatter radio signal reflectors is by using a switch, connecting sensor’s antenna to different loads. Elevating the above principles from sensing to networking of several, simultaneously operating, scatter radio sensors is not trivial and emerges as a challenging topic of research.

Work in [20] offered frequency-modulated scatter radio signals with soil moisture information and duty-cycled operation that reduced the operating bandwidth, while experimental results were reported for only two sensors and commodity software defined radio (with cost in the order of 1000 Euro). The tag-to-reader communication range was in the order of 100 meter. In this work, 50% duty-cycle of frequency modulated soil moisture is achieved with a new circuit, which also reduces the overall power consumption; 50% duty cycle is crucial for getting rid of even-order harmonics and thus, enhancing the available bandwidth for multiple scatter radio sensors simultaneous access [21]. Moreover, this paper offers a different, more accurate sensor calibration method. Moreover, this work offers experimental results for multiple sensors, ranges in the order of 250 m with ultra low-cost, portable SDR (that costs 7 Euro), while scalability issues are further examined.

A. Scatter Radio Principles

Scatter radio communication, known from 1948 [22], is currently exploited in the radio frequency identification (RFID) industry. Communication is implemented with an antenna, a control circuit and a radio frequency (RF) switch between them. The switch alternatively terminates the tag/sensor antenna between (usually two) loads $Z_1$ and $Z_2$ (Fig. 2). The control circuit is responsible for the modulation operation. Tag/sensor antenna $S_{11}$ parameter (i.e., reflection coefficient $\Gamma$), associated with each antenna terminating load, is modified when the antenna load is changed. The different termination loads offer different reflection coefficients, ($\Gamma_1$ and $\Gamma_2$) according to the following [23]–[27]:

$$\Gamma_i = \frac{Z_i - Z_a}{Z_i + Z_a},$$

with $i = 1, 2$ and $Z_a$ denoting the antenna impedance.

Therefore, amplitude and phase of the carrier signal induced at the sensor antenna - are modulated and the signal is reflected (scattered) back towards a receiver. As a result, when a continuous wave (CW) with frequency $F_c$ is incident on the sensor antenna, which is alternatively terminated between two loads at a rate $F_{sw}$, two new subcarrier frequencies appear in the spectrum (Fig. 2); their frequency values are given by [28]:

$$F_{\text{sub,1}} = F_c + F_{sw},$$

$$F_{\text{sub,2}} = F_c - F_{sw}. \quad (3)$$

While scatter-radio principles have been restricted to communication ranges of up to a few meter [29]–[31], a novel scatter radio sensor network (WSN) for relative humidity (%RH) measurements was presented in [32]. That WSN consisted of low-power and low-cost analog designs of wireless transmitters (sensor nodes/tags) with scatter radio and extended communication ranges. Each tag employed bistatic semi-passive scatter radio principles [33]. In order to address the small communication range problem, the WSN utilized the bistatic topology (where the carrier emitter was placed in a different location from the reader) and semi-passive (i.e., battery-assisted) tags. The utilization of the bistatic topology is illustrated in Fig. 3. Using the above concepts, it was shown possible to implement large-scale networks, comprising of low-cost sensor/tags, a few emitters operating at the European RFID band ($865 \text{–} 868$ MHz) [34] and a single software-defined radio (SDR) receiver, detecting the backscattered signals.

This work describes the development of a bistatic scatter radio WSN, that measures soil moisture percentage (%SM) with analog, frequency modulation (FM) principles and ranges in the order of 250 meter. In sharp contrast to prior art, this work offers a) custom capacitive sensing, b) soil moisture sensing and networking of multiple sensors (with corroborating experimental results), c) reception with ultra-low cost software-defined radio (SDR) that costs only a few Euro and d) special modulation design that offers scatter radio modulation signals with 50% duty cycle; the latter will be shown to be important for signal-to-noise ratio improvements at the SDR receiver, as well as for network scalability purposes.

Section II offers the design and implementation of the scatter radio sensor circuit, multiple access capability and power consumption tradeoff. Section III offers the SDR receiver design, based on a 8-bit ultra-low cost SDR. Section IV describes the simple calibration procedure and Section V offers the experimental results, including a relevant network demonstration and bistatic range measurements. Finally, work is concluded in Section VI.

II. SENSORS DESIGN AND IMPLEMENTATION

The design target of the tags is to produce voltage pulses of fundamental frequency that depends on the %SM value and control the rate with which the antenna termination loads are alternated. For this purpose, the circuit diagram of Fig. 4 was designed, consisting of a custom capacitive soil moisture sensor, the capacitance-to-frequency converter (C2F), the power supply circuit and the scatter radio front-end.
reduce consumption, while attaining pulses with duty cycle of 50%; the latter is a fundamental difference compared to other capacitance-to-frequency converters in the literature (e.g., [32]). The timer output square wave pulse is offered with fundamental frequency given by:

$$F_{sw} = \frac{1}{2 \ln(2) R_2 (C_p + C_{sm})}.$$  \hfill (4)

According to [36], the power of the fundamental subcarrier frequency of the scattered signal is given by:

$$P(a) = \left[ \frac{A \sqrt{2}}{\pi} \sin(\pi D) \right]^2,$$  \hfill (5)

where $A$ is the peak-to-peak amplitude of the pulse signal and $D$ is the duty cycle; thus, the backscattered signal power will be increased when $D$ approaches the value of 50%. Using a single analog switch (SW in Fig. 4) and only one resistor ($R_2$) in the typical astable multi-vibrator circuit, the duty cycle of the produced pulse is calculated as follows:

$$D = \frac{R_2}{2R_2} = 50\%.$$ \hfill (6)

According to its Fourier series analysis, a 50% duty-cycle square pulse consists of odd order harmonics of the fundamental frequency, i.e., even order harmonics are not present. Therefore, square waves without 50% duty-cycle occupy additional bandwidth, limiting the capacity of the designed network in a specific frequency band.

### B. Scatter Radio Antenna/Front-end

The scatter radio front-end of each tag (Fig. 5, right bottom) consists of a microstrip bow-tie antenna on low-cost FR-4 substrate with an embedded RF switch; the latter is the Analog Devices ADG902 [37], set up as SPST switch. The ADG902 was chosen due to its low insertion loss (0.8 dB at 1 GHz) and high isolation (43 dB at 1 GHz). The front-end design was tuned around 868 MHz, according to the maximization principles in [27].
A bowtie antenna for each sensor design was adopted, due to its omnidirectional attributes (at the vertical to its axe level) and the ease of fabrication, with nominal gain of \( G = 1.8 \) dBi. Fig. 5 offers dimensions. Such antenna is appropriate for the bistatic scatter radio topology, while a different printed antenna with higher gain could increase the ranging distance in the bistatic topology; however appropriate alignment during installation could be needed in that case.

C. Multiple Access

Simultaneous, collision-free operation of multiple, receiverless sensors is facilitated with frequency-division multiple access principles [21], [28], [32]; every tag is assigned a distinct frequency band (bandwidth), within which the switching rate (i.e., subcarrier frequency) of each tag’s antenna load can vary. Fig. 6 illustrates the concept with both conceptual and experimental data.

Let \( F_{sw,i}^L \) and \( F_{sw,i}^H \) denote the subcarrier frequency output of the i-th tag for lowest and highest frequency, produced by the C2F converter when the %SM is 100 and 0, respectively. The required bandwidth \( B_i \) depends on the above two frequencies and is calculated as:

\[
B_i = F_{sw,i}^H - F_{sw,i}^L. \tag{7}
\]

Assuming that \( C_L, C_H \) are the \( C_{SM} \) sensor capacitance for 0%, 100% SM, respectively, the \( C_{pj} \) and \( R_{2,i} \) components of i-th tag are calculated according to (4), (7) as:

\[
C_{pj} = \frac{B_i C_L + F_{sw,i}^L (C_H - C_L)}{B_i}, \tag{8}
\]

\[
R_{2,i} = \frac{B_i}{2 \ln(2) F_{sw,i}^L (C_H - C_L) (F_{sw,i}^L + B_i)}. \tag{9}
\]

It is noted that the outdoor environment temperature variations affect each sensor’s circuit operation. For example, the CSS555 timer exhibits a temperature drift of 40 ppm/°C and thus, for a tag/sensor with nominal subcarrier frequency at 105 kHz, an extreme change of 30°C in temperature offers a frequency drift of \( (40 * 30 * 10^5000)/10^5 = 126 \) Hz. For bandwidth of 1.5 kHz per sensor, the aforementioned frequency shift amounts to 126/1500 = 8.4% of each sensors bandwidth and a SM error in the same order. For ten times higher bandwidth per sensor, that drift would amount to only 0.84% error, with however reduced number of sensors in the available spectrum band. Thus, there is clearly a flexible tradeoff between scalability (in number of simultaneously operating sensors) and measurement accuracy.

For example, assuming operating (subcarrier) sensors’ frequencies in 100 kHz-299 kHz, guard band of 1 kHz (to avoid adjacent-channel interference between sensors) and 1.5 kHz bandwidth/sensor, the capacity of the network results to 79 sensors. The upper limit of 299 kHz is selected in order to avoid the odd order harmonic of the lower limit subcarrier frequency of 100 kHz. Future work will install low-cost envelope detector receivers in each sensor, so that a subset of the sensors operate simultaneously and thus, the same number \( M \) of subcarrier frequencies is shared by a larger number \( N \) of sensors, where \( N \gg M \) (resembling GSM network architecture, where the same frequency channel is used by 8 users in TDMA mode).

D. Power Consumption & Tradeoff

The power supply circuit of each sensor is a crucial part, since its lifetime depends on it. For this purpose, a voltage reference integrated circuit (IC) and a coin battery were utilized. The power source was a 300 mAh, 3 V lithium-ion battery (type CR2032), connected with the C2F converter through the voltage reference component (Texas Instruments (TI) REF3318, [38]). The voltage reference consumed 5 uA only and supplied with stable voltage \( (V_{cc}) \) the whole circuit.

The total power dissipation of each sensor is calculated below:

\[
P_{\text{sensor}} = P_{\text{charge}} + P_{\text{quiescent}}, \tag{10}
\]

with \( P_{\text{charge}} \), the average power required for charging the capacitors and \( P_{\text{quiescent}} \), the quiescent power dissipated by the timer and the voltage reference IC. The components that were utilized in the sensor design consumed quiescent power of...
The fundamental subcarrier frequency $\hat{F}_i$ of the i-th sensor was estimated using the periodogram technique, which in turn is grounded on maximum likelihood principles. The estimated subcarrier was given according to:

$$\hat{F}_i = \arg\max_{F \in [F_{sw,i}^L, F_{sw,i}^H]} |X(F)|^2,$$

where $X(F)$ is the Fourier transform of the baseband down-converted and carrier frequency offset (CFO)-compensated signal. CFO estimation and compensation was based on standard periodogram techniques [41]. $F_{sw,i}^L$ and $F_{sw,i}^H$ mark the a-prioi known lowest and highest possible frequency output of the i-th tag. Thus, the frequency component with the maximum power at each spectrum band is estimated as the corresponding sensor’s output frequency.

### IV. Calibration

Deviations from nominal values of each tag’s components (e.g., tolerance of capacitors, resistor or timer), as well as temperature dependence, require compensation, i.e., sensor calibration; the tags of this work were calibrated using polynomial surface fitting, utilizing both %SM and temperature parameter as input variables, as described below.

A soil sample was taken from the field, dried and filled a 1000 cubic centimetre (cc) container. Specific mass of water (in grams) was poured into the container and soil moisture percentage by volume was calculated, according to the following:

$$\text{Soil Moisture (\% by Volume)} = \frac{\text{Volume of Water}}{\text{Volume of Soil}} \times 100,$$

(13)

with

$$\text{Volume of Water} = \frac{\text{Mass of Water}}{\text{Density of Water}},$$

(14)

with (well-known) density of water equal to 1 gram per cc.

Using the sensor design and the WSN reader described above, samples of subcarrier frequency were collected, for fixed temperature and variable soil moisture % (or vice-
versa). Working with 226 sets of measurements (subcarrier frequency, temperature and soil moisture), minimum mean square error (MSE) cubic polynomial fitting was applied between subcarrier frequency, %SM and temperature. The outcome polynomial is given in Table II with corresponding fitting root mean squared error (RMSE). The surface (3D) transfer function is shown in Fig. 8 and a special case for fixed temperature 18.4°C, (2D) transfer function is shown in Fig. 9.

Fig. 9 shows an interesting saturation effect (at the output frequency), when the soil moisture by volume reaches 48%. That is due to the hydraulic properties of all soil textures. Specifically, “total pore space, expressed on a volumetric basis, ranges from 40% in sandy soil to 48% in clay soil. When a soil is completely saturated, all the pores are filled with water. Thus, porosity is also the water content at saturation, expressed as the volume of water per volume of soil.” [42, chapter 6 “Soils”, p. 167]. Thus, the observed saturation above 48% of the sensor is clearly coherent with the physical phenomenon of water content in various soil textures and thus, an indirect indication that the sensor is working properly.

Measured %SM results using the above procedure of (13), (14) were compared with the sensor’s output; for data of Fig. 9 (fixed temperature), root mean squared error (RMSE) of 0.15% SM and mean absolute error (MAE) of 0.13% SM were found. Such error will be denoted as calibration error, since it does not include the error due to scatter radio communication, studied below.

<table>
<thead>
<tr>
<th>Model</th>
<th>Fitted function</th>
<th>RMSE</th>
</tr>
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<tbody>
<tr>
<td>3D</td>
<td>$f(x,y) = 105.5 + 0.232x + 0.0121y - 0.0074x^2$</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>$+ 0.0020xy - 0.0036y^2 + 7.531 \times 10^{-5}y^3$</td>
<td>(kHz)</td>
</tr>
<tr>
<td></td>
<td>$- 2.94 \times 10^{-7}x^3 + 2.08 \times 10^{-6}x^2y + 3.65 \times 10^{-5}y^3$</td>
<td></td>
</tr>
</tbody>
</table>

V. EXPERIMENTAL RESULTS

Fig. 5 (right picture) depicts one of the fabricated sensor tags with low-cost FR-4 material and cost on the order of 6 Euro. At the installation site, each backscatter sensor node’s bow-tie antenna (with its scatter radio front-end) was located well above the ground, while the fabricated capacitive sensor was inserted into the soil (Fig. 10) and the connection between those two parts was established with cables. The implemented demonstration WSN consisted of 18 scatter radio soil moisture sensors nodes, which could operate simultaneously, without collisions; Fig. 6 depicts the obtained sensors subcarriers and the emitter carrier at 868 MHz. Each sensor was allocated a unique 0.5 to 1.5 kHz frequency band (bandwidth) and there was a guard-band of 1 kHz between neighbouring-in-frequency tags to alleviate adjacent channel interference. Fig. 6 illustrates the subcarriers corresponding to 0% SM.

For demonstration purposes, a subset of the network was deployed in the indoor garden of Technical University of Crete. The bistatic topology scatter radio WSN with eight sensor nodes is depicted in Fig. 10. Carrier emitter (E) and RTL-SDR reader (R) were located at either sides of the field with the sensors in between. Capacitive sensors were inserted into the soil near the root of each plant, while the scatter radio front-ends were placed 1.5 meter above the ground, using canes.

Sampled data time series collected from approximately seven hours of continuous monitoring are illustrated in Fig. 11. It can be easily observed that after the watering instances, the output frequency of the sensors changed instantly, while it settled after a limited amount of time.

In order to achieve both communication performance characterization and sensing accuracy of the proposed WSN, maximum communication range and end-to-end sensing accuracy were experimentally measured. Specifically, a complete bistatic topology link was utilized outdoors (Fig. 12).

Carrier emitter, SDR receiver and sensor/tag (with subcarrier center frequency at 109 kHz) were installed at 1.3 m height. Temperature of 18°C was measured, soil moisture was fixed at 0% SM (corresponding to 109 kHz subcarrier frequency for the specific sensor), sampling rate was set to
1 MHz and duration of 100 ms was exploited per sensor measurement. Communication performance was tested for various installation topologies and the corresponding results, in terms of estimating the transmitted subcarrier frequency, are presented in Table III, as a function of emitter-to-tag distance ($d_{et}$), tag-to-reader distance ($d_{tr}$) and root mean squared error (RMSE) in Hz, after 1000 measurements, for each case (row) of Table III. Reference subcarrier value was measured with carrier emitter and SDR receiver in closed proximity with the sensor (and all the rest of the parameters the same), using average value out of 1000 sensor measurements.

Sensor-receiver ranges in the order of 250 meter are possible, with limited RMSE error in the order of 0.1%, due to wireless communication. Such small communication error suggests that communication ranges could be further increased and scatter radio communication range is not an issue. A similar finding, based on proper designs for scatter radio reception, has been also recently reported in [43]–[45]. Therefore, the overall sensor error is upper bounded by the sum of the RMSE calibration and communication errors under mild assumptions (e.g., independence of noise in sensor and noise in receiver, unbiased errors etc.), which for the above values of Table III and the results of Section IV offers overall RMSE below 1% SM. Finally, it is noted that for all experimental results, emitter transmission power was 13 dBm at 868 MHz.

VI. Conclusion

This work described in detail the development of a scatter radio network of low-power and low-cost sensors of soil moisture. Communication ranges in the order of 250 meter were experimentally demonstrated, with overall RMSE, less than 1%. Scaling issues were also discussed. The low power consumption of each scatter radio sensor, in the order of 200
microWatts, enabling powering from ambient energy sources (including RF and thermoelectric), left for future work.

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REFERENCES


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