Converting a Plant to a Battery and Wireless Sensor with Scatter Radio and Ultra-Low Cost

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***Abstract*—Electric potential (EP) signals are produced in plants through intracellular processes, in response to external stimuli (e.g., watering, mechanical stress, light, and acquisition of nutrients). However, wireless transmission of a massive amount of biologic EP signals (from one or multiple plants) is hindered by existing battery-operated wireless technology and increased associated monetary cost. In this paper, a self-powered batteryless EP wireless sensor is presented that harvests near-maximum energy from the plant itself and transmits the EP signal tens of meters away with a single switch, based on inherently low-cost and low-power bistatic scatter radio principles. The experimental results confirm the ability of the proposed wireless plant sensor to achieve a fully autonomous operation by harvesting the energy generated by the plant itself. In addition, EP signals experimentally acquired by the proposed wireless sensor from multiple plants have been processed using nonnegative matrix factorization, demonstrating a strong correlation with environmental light irradiation intensity and plant watering. The proposed low-cost batteryless plant-as-sensor-and-battery instrumentation approach is a first but solid step toward large-scale electrophysiology studies of important socioeconomic impact in ecology, plant biology, and precision agriculture.**

***Index Terms*—Energy harvesting, plant, scatter radio, wireless sensor network (WSN).**

I. Introduction

CONSTANT monitoring of microclimate parameters in agricultural fields is important for efficient irrigation, fertilization, and production management. Thus, wireless sensor networks (WSNs) suitable for agricultural applications have been developed, in order to measure soil moisture, barometric pressure, as well as ambient humidity and temperature [1]–[5]. In [6], an image capture WSN node is presented for detecting certain pests that affect the crops, while in [7], a WSN is deployed for indoor and outdoor air quality monitoring.

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The existing wireless telemetry technology typically accommodates only one sensor for an extended area within an agricultural field, spanning multiple plants. According to [1]–[7], the existing WSN nodes for agricultural and environmental applications comprise microcontroller-based units in order to measure and process the sensory data, while the energy required for their operation is usually produced by solar panels and/or batteries. The WSN nodes transmit their measurements to a data acquisition station, by employing WiFi- or IEEE 802.15.4-based protocols (e.g., ZigBee). In the case of remote agricultural applications (e.g., in greenhouses), the data acquisition station that collects the measurements of the individual WSN nodes may also communicate with a central server (e.g., for data storage in a database and interface with a client application software) through a Global System for Mobile communications/General Packet Radio Service-based data transmission link.

On the other hand, it has been understood that each plant's intracellular processes produce electric potential (EP) signals [8]–[11], in response to external stimuli, including acquisition of nutrients, pH and light, and mechanical stress (e.g., wounding) [12]–[14], as well as temperature and watering variations [13], [15]. More specifically, it has been shown that wound-activated surface potentials propagate to distal leaves, depending on the plant vascular connections (also known as parastichies), with speeds on the order of a few centimeters/meters, and concomitant activation of specific regulatory lipid agents in the propagating path. Deciphering the underlying regulating genes of such plant self-induced electric defense sensing system is under intense research investigation [12], [14]. Plant light perception is another example of critical plant self-induced sensing; phytochromes are one class of the plant's major transducing photoreceptors, able to change color depending on whether red or far-red light is absorbed or reflected from neighboring plants [9]. Phytochromes provide plants with temporal signals that entrain their circadian rhythm, and due to their sensitivity to reflected light from neighboring plants, they are viewed as mediators for proximity sensing of other potentially competing plants [9].

Therefore, plants can be treated as sensors, enabling direct sensing of their physiology, instead of estimating it indirectly through measurements acquired by sensors installed in the surrounding environment of the plant (e.g., estimating the irrigation requirements of a plant using the measurements of a soil moisture sensor). There is fertile literature on electrophysiology studies [8], [13], [15]–[17] relevant to the rich plant (either action or variation) EP mechanism that could elevate the plant-as-sensor idea. However, wireless transmission of a massive amount of EP signals (from one or multiple plants) is hindered by the existing battery-operated wireless technology and increased the associated monetary cost of conventional Marconi-type radios (see [1]–[7] described above), typically requiring limited efficiency amplifiers as well as power-demanding signal conditioning units, such as mixers and active filters. As analyzed in [18], the use of batteries as energy storage devices increases the construction and maintenance costs of wireless sensors. Thus, treating plant-as-battery, i.e., harvesting energy from plants, is another potentially powerful idea, which, however, has not been fully exploited so far.

Batteryless telemetry designs have exploited solar, magnetic [19], kinetic [20], [21], radio frequency (RF) [22]–[25], thermoelectric [26], [27], and wind [28], [29] energy harvesting techniques, combination of them [30], as well as biologic batteries, e.g., from the inner ear [31], soil [32], or the stem of a plant or tree [33], [34]. However, these designs typically suffer from limited communication range, scalability, and/or cost. Moreover, energy harvesting from plants has not exploited so far maximum power point (MPP) tracking principles. An additional hindrance of employing these forms of energy production schemes in precision agriculture applications, where a large number of sensing nodes are desirable within the crop field, is that they are rather intermittent in terms of availability, i.e., energy is either scarce (e.g., ambient RF and magnetic energy) or completely absent during prolonged time intervals within a day (e.g., solar, kinetic, thermoelectric, and wind energy).

Finally, existing research in the area of correlating the electrical signals generated by plants with their physiology, external stimuli, and environmental conditions has been conducted only at small scale, mostly at the laboratory level [16], [17]. This is due to the existing lack of appropriate instrumentation technology, which would enable the deployment of low-cost and large-scale data acquisition equipment for continuously monitoring the electrical signals generated by multiple plants in their natural habitat. Targeting to fill this gap, it is demonstrated in this paper for the first time in the existing research literature as to how an avocado (*Persea americana*) plant can be converted to a batteryless wireless sensor of environmental light and irrigation, harvesting and storing energy from itself. For that purpose, the design of a self-powered batteryless EP wireless sensor is presented in this paper, which performs the following.

1) Measures the EP signal generated by the plant under monitoring.
2) Transmits the EP signal with a single switch, based on inherently low-cost and low-power bistatic scatter radio principles.
3) Harvests near-maximum energy from the plant itself for supplying power to the wireless plant sensor electronic circuits, thus achieving a fully autonomous operation.

The wireless sensor node per plant with analog bistatic scatter radio, which is proposed in this paper, does not require amplifiers, mixers, or active filters, such as those typically employed in conventional Marconi radio technology, as in Bluetooth, WiFi, or ZigBee-based protocols [1]–[7], [21], [28], [29], [32], [33], [35]. Instead, this paper employs a voltage-controlled oscillator (VCO) that converts the plant EP signal to a periodic square-wave signal driving a single RF switch connected to an antenna; thus, the plant EP signal modulates the reflection coefficient of the antenna. Then, by illuminating the wireless plant sensor antenna with an electromagnetic wave—stemming from a remote emitter—and receiving the reflected EP-signal-modulated wave at a remote software-defined radio (SDR) receiver, the EP signal can be recomposed with frequency-based maximum likelihood (i.e., periodogram) demodulation techniques. As demonstrated in the experimental results, by adopting this communication technology, the power consumption of the proposed wireless plant sensor is reduced to a significantly low level and simultaneously a relatively long operational communication distance can be achieved. Furthermore, simultaneous data acquisition from multiple plants (e.g., in greenhouses and outdoor fields) is possible by building a WSN that consists of the proposed wireless plant sensors, where a different range of switching frequencies is allocated at the individual wireless sensors installed in various plants subject to monitoring.[1] A fully functional experimental prototype of the proposed wireless sensor node has been developed. The experimental results demonstrate the ability of the proposed wireless plant sensor to achieve a fully autonomous operation by harvesting the energy generated by the plant itself and confirm the correlation of the EP signals generated by an avocado plant with environmental light irradiation intensity and plant watering, which may provide hints for appropriate automated plant irrigation.

Since the operation of the proposed wireless plant sensor does not depend on the type of plant subject to monitoring and it is not affected by its cultivation needs, the proposed instrumentation platform can be employed for building WSNs, which monitor agricultural installations comprising multiple different types of plants. The proposed low-cost batteryless wireless approach offers proof of concept for the plant-as-sensor-and-battery idea. In addition, it advances the current instrumentation technology in the field of plant monitoring by enabling the conduction of large-scale and low-cost plant electrophysiology studies (which are currently not feasible, as discussed above) of important socioeconomic impact in ecology, plant biology, as well as precision agriculture.

This paper is organized as follows. The characteristics of plants as an energy source are discussed in Section II. The instrumentation design of the proposed plant-powered wireless sensor is analyzed in Section III, while the implementation and experimental measurement results are presented in Section IV. Finally, the conclusions are drawn in Section V.

II. Harvesting Energy From the Plants

An analysis of the plant as an energy source was conducted in [33] and [34] for Pachira and bigleaf maple trees, respectively. However, in these studies, the actual form of the plant

[1]Receiver ranges on the order of 90 or 150 m have been recently reported experimentally, with analog [36] or digital bistatic semipassive scatter radio [37], [38], respectively.

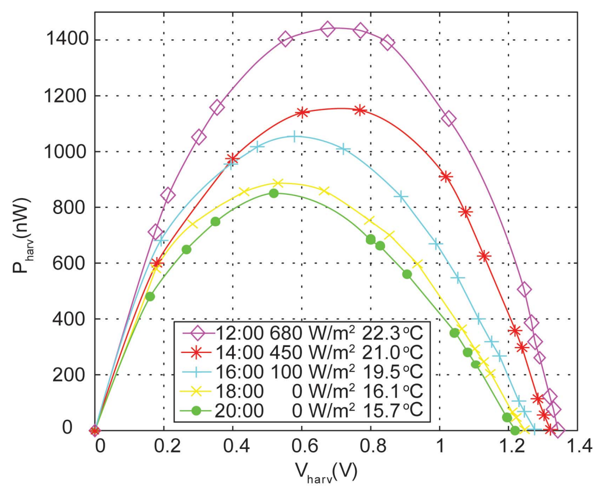


Fig. 1. Power–voltage characteristics of the electrical signal generated by an avocado tree during a day and the corresponding values of solar irradiation and ambient temperature.

power–voltage characteristic was not explored. Fig. 1 shows the experimentally measured power–voltage characteristics of an avocado plant (*P. americana*) during a day. In this work, zinc anode alloy in combination with a copper cathode was used for the electrodes connected to the power harvesting circuit, offering a high open-circuit voltage without significant degradation over time. The power–voltage characteristics form concave curves with a unique MPP, where plant-generated power is maximized. The power harvested from the plant is equal to $P_{\text{harv}} = I_{\text{harv}} \cdot V_{\text{harv}}$, where I_{harv} denotes the current sourced when the voltage across the plant harvesting electrodes is V_{harv}. It is observed that the MPP position on the plant power–voltage characteristic varies in the range 0.52–0.67 V, depending on the solar irradiation and ambient temperature conditions. The maximum generated power varies from approximately 800 nW to above 1400 nW throughout the day. The power capacity of such figures was exploited in the overall design of the proposed wireless sensor, as explained in Section III.

III. Design of the Proposed Self-Powered Wireless Sensor

The proposed wireless plant sensor has been designed such that the ability of a plant to produce electric signals is exploited for both energy supply and EP signal sensing purposes. A block diagram of the proposed self-powered wireless sensor is shown in Fig. 2, which consists of the power management, signal conditioning, and RF communication units. The power management unit harvests the plant-generated energy for supplying power to the electronic circuits of the proposed wireless sensor. The signal conditioning unit performs the necessary signal conditioning and frequency modulation of the plant signal. The RF communication unit executes the backscatter operation that encapsulates the modulated information into the remotely transmitted carrier signal and scatters back the modulated information.

A. Power Management Unit

As analyzed in Section II, a very low amount of power is produced by the plant. In order to exploit it for supplying power to the signal processing and RF communication circuits of the proposed wireless plant sensor, which consume a much higher amount of power, an input energy storage capacitor (C_{in} in Fig. 2) is employed to periodically accumulate the energy produced by the plant according to the following operating scheme: during charging of C_{in}, the operation of the signal conditioning and RF front-end subsystems is suspended, such that the voltage and energy stored in C_{in} rise progressively; after sufficient energy has been accumulated in C_{in}, rising the voltage across its terminals to the appropriate level, the power management unit is reactivated, providing the electric energy stored to the signal conditioning and RF front-end subsystems, which by consuming the plant-generated energy previously accumulated in C_{in} restart to condition and wirelessly transmit the plant EP signal. This charging/discharging process is repeated iteratively, determining the duty cycle, D, of the proposed wireless sensor operation, which is defined as follows:

$$D = \frac{t_{\text{ON}}}{T_{\text{op}}} = \frac{t_{\text{ON}}}{t_{\text{ON}} + t_{\text{OFF}}} \tag{1}$$

where t_{ON} is the transmission time interval (ON state) of the wireless sensor, T_{op} is the repetition period of the C_{in} capacitor charging/discharging process, and t_{OFF} is the time interval that the wireless sensor operates in the OFF state, where capacitor C_{in} is charged and the signal conditioning and RF front-end units are deactivated. Any variability of the amount of energy produced by the plant (e.g., due to the plant type and the daily and seasonal variations of plant physiology) will affect the time required to recharge capacitor C_{in} as well as the transmission time interval [i.e., t_{ON} in (1)] of the proposed wireless plant sensor, thus affecting the sampling rate of the EP signal measurements transmitted to the remote data collection receiver. However, the operational capability of the proposed wireless plant sensor will not be degraded. The capacitance of C_{in} is selected such that even when operating with the minimum value of t_{ON} in (1), the resulting rate of measurements transmitted to the data acquisition unit satisfies the target application specifications. In addition, by designing the dc–dc power converter to operate in the dc input voltage range 0.5–0.7 V, as analyzed in the following, the power generated by the plant is kept close to the corresponding MPP in the time-varying power–voltage curves during the day (Fig. 1). Thus, a nearly optimal exploitation of the available biologic energy of the plant is achieved, and as a result, the time interval required for charging capacitor C_{in} is minimized.

The power management unit includes a voltage detector, consisting of two cascaded CMOS inverters with positive feedback in Schmitt trigger mode, which is based on a modification of the design presented in [39], in order to achieve operation at ultralow input power. The CMOS inverters are directly supplied power by the input energy storage capacitor (i.e., C_{in} in Fig. 2). The voltage detector circuit continuously monitors the capacitor voltage V_{harv}, keeping the load

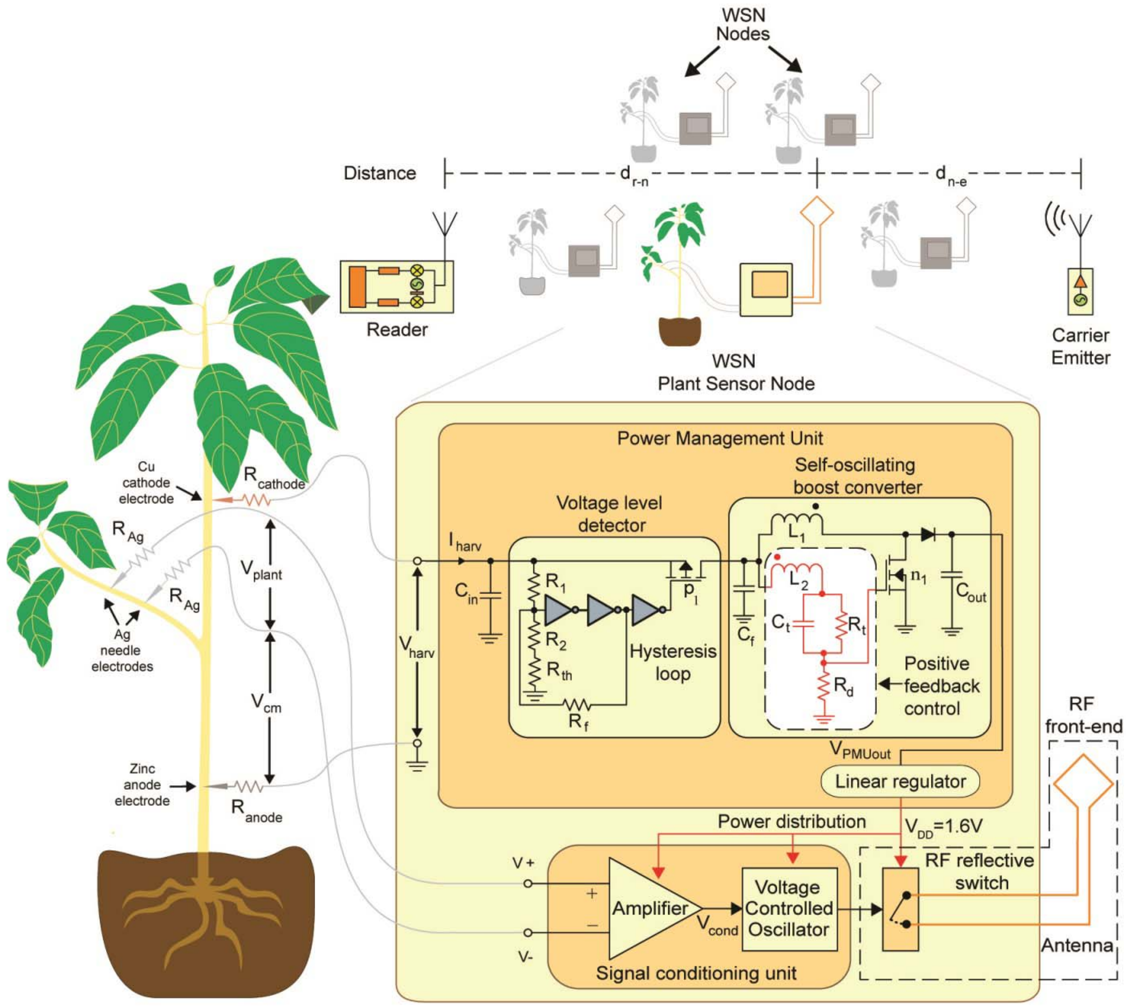


Fig. 2. Schematic of the proposed self-powered wireless sensor, as well as the experimental topology.

(i.e., the signal conditioning and RF front-end units) electrically isolated from the plant power source, during charging of C_{in}. The power management unit is activated when the dc input voltage V_{harv}, which is produced by the plant (Fig. 2), is between the preset thresholds V_H and V_L, imposed by the voltage detector. During the time interval that the electrical signal generated by the plant is lower than V_L, the input capacitor is isolated from the signal conditioning and RF front-end units. In that state, resistor R_f operates as being electrically connected in parallel with R_2, while transistor p1 remains in the OFF state. When threshold V_L is reached, resistance R_1 operates electrically in parallel with R_f and transistor p1 is turned ON. Thus, a response with hysteresis is exhibited. When the voltage of capacitor C_{in} (Fig. 2) reaches the V_H threshold, the voltage detector ignites the operation of the dc–dc power converter and the energy stored in the capacitor flows to the load, which consists of the signal conditioning and RF front-end units. The dc–dc converter steps up the voltage of C_{in} to the level required by the voltage regulator to operate. The electronic components comprising the signal conditioning and RF front-end units of the proposed wireless plant sensor have been selected such that they are all capable to operate successfully when supplied power through the output voltage produced by the voltage regulator (i.e., V_{DD} in Fig. 2). Thus, the use of multiple power sources is avoided, simplifying the design of the proposed system. The signal conditioning and RF front-end units operate for t_{ON} duration until capacitor C_{in} discharges so that its voltage reaches the value of the V_L threshold. Then, the voltage detector terminates the energy flow from the dc input capacitor toward the power converter.

The sensitivity of the upper and lower thresholds with temperature is compensated for by integrating a negative temperature coefficient thermistor (R_{th} in Fig. 2) and appropriately selecting resistors R_1 and R_2. Thus, the temperature compensation range can be adapted to the ambient temperature conditions of the target installation site. The dc–dc power converter circuit proposed in [40] was employed and designed such that it is able to step up a dc input voltage with a minimum level of 520 mV.

B. Signal Conditioning Unit

The measurement of the EP plant signal is performed by inserting Ag needle electrodes into the plant stem or branch. In contrast to the glass pipettes containing Ag/AgCl wires in KCl solution, which could also be attached on the plant stem or branch as an alternative configuration for measuring the plant-generated voltage [16], the Ag needle electrodes do not exhibit performance degradation after long-term usage and also it is not required to periodically recalibrate them. Thus, a wound-based measurement is performed by the proposed wireless plant sensor, achieving long-term stability, without being deteriorated by the performance degradation of the EP signal sensing electrodes.

The EP signal of the plant V_{plant} is developed across the Ag needle electrodes. As shown in Fig. 2, a common-mode voltage V_{cm} is developed between V_{plant} and the ground reference electrode of V_{harv} that is used for energy harvesting, as analyzed in Section III-A. The plant-generated signal is amplified using a triple-op-amp instrumentation amplifier (IA), featuring a high input impedance and a high common-mode rejection ratio. Then, a VCO is used to modulate in frequency the IA output voltage (i.e., V_{cond} in Fig. 2). A square-wave signal is produced by the VCO, which is used to control the switch of the RF front end for implementing the backscattering-based wireless communication functionality, which is described in the next paragraph. The modulation frequency of the VCO output signal (i.e., the switching frequency of the RF front-end antenna) F_{mod} (Hz) is given by the following equation:

$$F_{\text{mod}} = G_1 \cdot (1 - V_{\text{cond}}) \tag{2}$$

where

$$V_{\text{plant}} = V_+ - V_- \tag{3}$$

$$V_{\text{cond}} = G_2 \cdot (V_+ - V_-) + V_{\text{ref}} \tag{4}$$

and V_{plant} is the plant EP signal developed across the Ag needle electrodes, V_{cond} is the IA output voltage, V_+ and V_- are the potentials of the plant sensing electrodes with respect to the ground level (Fig. 2), and V_{ref} is a reference voltage used to offset the value of F_{mod} in (2) at the desired central frequency F_c [i.e., $F_c = F_{\text{mod}}|_{V_{\text{plant}}=0} = G_1 \cdot (1 - V_{\text{ref}})$], while gains G_1 and G_2 are determined by the values of the circuit components.

As will be demonstrated in Section IV, the value of V_{plant} may be either positive or negative during a day, depending on the plant physiology. In such a case, the value of F_{mod} is shifted above or below F_c according to (2)–(4).

C. Scatter Radio Unit

As shown in Fig. 2, the square wave produced by the VCO controls a RF switch affecting the amount of electric load seen by the antenna and, consequently, its reflection coefficient. During the operation, the antenna is illuminated with an electromagnetic wave, which stems from a remote emitter (i.e., carrier emitter in Fig. 2). When setting the RF switch alternatively to the ON and OFF states, as dictated by the frequency of the VCO-generated square-wave signal (2)–(4), the reflection coefficient of the antenna is also altered with the same frequency [36]–[38]. Through this process, the plant EP signal measurements are frequency modulated into the electromagnetic wave reflected by the antenna, thus achieving their wireless transmission. The electromagnetic wave reflected by the antenna of the proposed wireless plant sensor is then received by a remote, SDR receiver, which comprises the data acquisition unit of the WSN (i.e., the reader in Fig. 2). The reader estimates the switching frequency of the RF switch, which is related to the plant EP signal according to (2)–(4), using maximum likelihood estimation with periodograms [36]. Simultaneous access from multiple plants is possible using different ranges of switching frequencies across different plants.

In the conventional Marconi-type radio technology (e.g., Bluetooth, ZigBee, and WiFi), wireless communication is achieved through the active transmission of electromagnetic energy emanating from the transmitter itself. In contrast, in the backscattering-based communication technique described above, the wireless plant sensor passively reflects only electromagnetic energy, which has initially been transmitted by an external device (i.e., the carrier emitter in Fig. 2). Thus, communication energy is consumed at the RF front end only for controlling the RF switch modulating the reflection coefficient of the wireless sensor antenna. As demonstrated in [36], by applying this communication principle, the energy supply requirements of the sensory data transmitter are reduced to a significantly lower level compared with those of conventional Marconi-based transmitters. This feature is also verified in the experimental results presented in the following.

The ambient temperature is measured by the reader, in order to compensate for the plant sensors' modulation-frequency drift with temperature. For that purpose, a third-degree polynomial of ambient temperature is used, which has been extracted with least squares data fitting through a temperature sensitivity characterization process. Additional necessary features were implemented to handle the sporadic transmission of the plant sensor measurements. Specifically, detection of the modulated EP signal start was performed with continuous energy calculation of sample sequences having a 100-ms duration each and then compared with a predefined threshold; the latter was defined using noise energy calculation, i.e., signal energy when the plant sensors did not transmit.

D. Plant Signal Processing

To reduce the noise present in the recorded plant signals, an undecimated wavelet shrinkage technique with a soft threshold estimator was used. The soft threshold estimation was based on Stein's unbiased estimate of risk [41]. Consequently, the plants' EP signals were normalized to the [0, 1] interval and combined into a monitoring signal matrix $\boldsymbol{X}$. Each row of matrix $\boldsymbol{X}$ contains a time series of EP signal measurements from a different plant. In order to identify the common factors that influence the electrical conditioning of all plants, nonnegative matrix factorization (NMF) [42], [43] was exploited, i.e., finding the positive semidefinite matrices $\boldsymbol{V}$, $\boldsymbol{W}$ corresponding (qualitatively) to the components and (quantitatively) to their weight, respectively, such that $\boldsymbol{X} = \boldsymbol{W}\boldsymbol{V}$. The solution to this problem is provided via minimizing a

Fig. 3. Experimental prototype of the proposed self-powered wireless sensor, constructed using off-the-shelf electronic components.

divergence function between $\boldsymbol{X}$ and the product $\boldsymbol{X} = \boldsymbol{WV}$, under the positive-semidefinite (nonnegative) constraints. In this study, an alternating least squares (ALS) NMF approach was used [42].

IV. Experimental Results

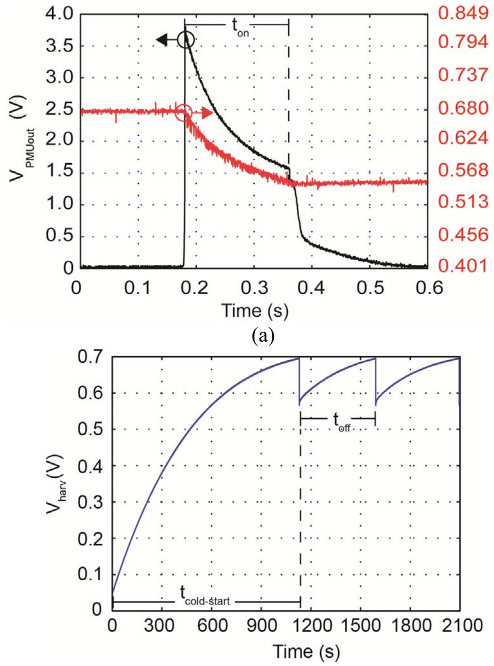
Multiple fully functional experimental prototypes of the proposed self-powered wireless sensor have been constructed using off-the-shelf electronic components and one of them is shown in Fig. 3. For measuring the EP plant signal, Ag needle electrodes of a 11-mm length and a diameter of 0.65 mm were employed. The two electrodes were inserted into a branch of the plant at a distance of 20 cm between each other in order to obtain an EP plant signal of sufficiently high amplitude [8]. The IA has been implemented with the MCP604x operational amplifier family that offers ultralow consumption and ultralow input current bias, which is crucial to the signal condition of the weak plant signals. In addition, an auxiliary op-amp was employed for adjusting the dc offset at the IA output, in order to enable tuning multiple wireless sensors, which comprise a WSN in star topology for monitoring multiple plants, at different switching frequency ranges. The signal conditioning unit also comprises a TS3002 timer, configured to operate as a VCO. The RF unit consists of the low-power single ADG902 wideband CMOS switch connected to an omnidirectional monopole antenna, which covers the needs of the agricultural wireless sensing application under study. The total power consumption of the signal conditioning and RF front-end units of the proposed plant sensor has been experimentally measured to be equal to 10.6 μW, even though the overall design is built with off-the-shelf electronic components. Since power is consumed at the RF front end only for controlling the RF switch, which modulates the reflection coefficient of the antenna, as described in Section III-C, this power consumption remains constant during the operation of the proposed wireless plant sensor. Such an ultralow power consumption has been achieved by: 1) using integrated circuits with ultralow power supply requirements (e.g., operational amplifiers and timer) for implementing the proposed wireless sensor and 2) employing the backscattering principle for implementing the RF front end, according to Section III-C. The total cost for constructing the proposed plant EP sensor in quantities of 100 pieces is approximately €8.70.

In order to calculate the required thresholds, V_H and V_L, respectively, of the voltage detector incorporated in the power management unit, as analyzed in Section III-A, the plant power–voltage curves (Fig. 1) were considered. In the experimental prototype circuit of the proposed wireless sensor, the values of $R_{\text{th}} = 5.6$ MΩ, $R_1 = 5.8$ MΩ, and $R_2 = 3.3$ MΩ were employed (see Fig. 2), resulting in the variation of V_H and V_L in the ranges 703–635 mV and 553–544 mV, respectively, for a 2.0 °C–29.0 °C ambient temperature change. The transmission time interval t_{ON} controls the received signal-to-noise ratio (SNR) at the receiver/reader and varies between 236–153 ms, for ambient temperature values in the range 2.0 °C–29.0 °C.

For minimizing the power losses during the high-frequency operation of the dc–dc converter, the coupled inductors L_1 and L_2 in Fig. 2 were implemented in the form of a planar coreless transformer with $L_1 = 13$ μH and $L_2 = 12.3$ μH. The values of R_t, C_t, and C_{out} in the positive feedback control oscillating tank were set to 330 Ω, 6.8 nF, and 9.2 nF, respectively. The resistance R_d in Fig. 2 was replaced by the gate input resistance of a BSH105 MOSFET, which was used as transistor n1. The electric resistance of the Ag needle electrodes and wires (R_{Ag} in Fig. 2) used to acquire the plant-generated voltage was measured to be equal to 0.064 Ω. The electric resistances of the anode and cathode harvesting electrodes and wires (R_{anode} and R_{cathode} in Fig. 2) were measured at 0.066 Ω and 0.057 Ω, respectively.

An avocado plant has been chosen as a reference in this paper for experimentally evaluating the performance of the proposed wireless plant sensor under real-life operating conditions, since plants of this type are frequently cultivated around the world for commercially exploiting their crops, primarily through the food industry.

The unregulated output voltage of the dc–dc Boost-type power converter during the operation of the power management unit is presented in Fig. 4(a). In order to evaluate the performance of the proposed instrumentation system under real-life operating conditions, the proposed wireless plant sensor was supplied power by the energy harvested from the avocado plant during that experimental process, as analyzed in Section III-A. Since the power converter operates without an embedded regulation capability, an initial overshoot arises. Fig. 4(b) shows the fluctuation of the dc input capacitor voltage (i.e., power management unit), depicting the time $t_{\text{cold-start}}$ needed for the overall system to start operating the first time (i.e., from cold start). After the cold start time $t_{\text{cold-start}}$, spanning about 1130 s, the input capacitor voltage fluctuates between the V_H and V_L thresholds. During the t_{OFF} time interval, capacitor C_{in} is charged toward the V_H level by accumulating the plant-generated electrical energy. This procedure restarts after the capacitor has been discharged to the predefined level (i.e., V_L). The duty cycle value as calculated in (1), indicated in Fig. 4(a) and (b), is 3.80×10^{-4}.



(a)

(b)

Fig. 4. (a) Unregulated output voltage of the dc–dc Boost-type power converter during the operation of the power management unit. (b) Duty cycle operation of the proposed self-powered wireless sensor, where the input voltage fluctuates between the V_H and V_L thresholds.

TABLE I

EXPERIMENTALLY MEASURED TRANSMISSION TIMES OF THE PROPOSED WIRELESS SENSOR FOR VARIOUS VALUES OF THE INPUT CAPACITOR

C_{in} (μF)	2350	2820	3350	3820	4350
t_{on} (ms)	176	194	247	266	274

TABLE II

SNR AND MEASUREMENT ERROR FOR TWO ALTERNATIVE BISTATIC TOPOLOGIES

Topology		*SNR*	*Error*	
$d_{r\text{-}n}$ *(m)*	$d_{n\text{-}e}$ *(m)*	*(dB)*	*RMS (mV)*	*MAE (mV)*
14.6	13.3	25.57	16.04	14.58
19.3	16.4	23.80	25.40	25.35

The power conversion efficiency of the power management unit is 1.1% when operated at $V_{\text{harv}} = 589$ mV. The experimentally measured transmission times of the proposed sensor node for various values of the input capacitor C_{in} are presented in Table I. It is observed that by increasing the value of C_{in}, the transmission time of the proposed wireless sensor is also increased.

Fig. 5 shows the spectrum of the signal received by the reader during the backscatter-based communication with two identical plant sensors, which transmit plant EP signal measurements of −600 mV and +600 mV, respectively. The gain G_1 in (2) was set at 67.34×10^3 and 74.87×10^3, respectively, at these two wireless sensors, while $G_2 = 0.1$ was set at both sensors. Thus, the frequency bands occupied

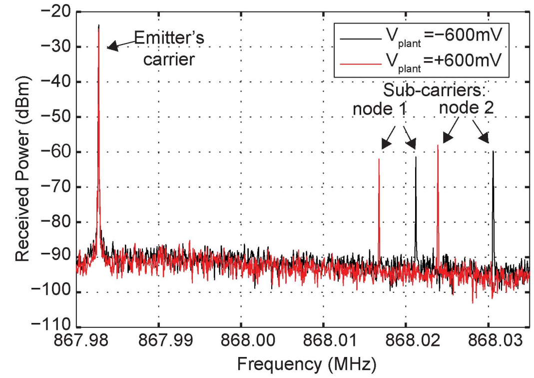


Fig. 5. RF emitter carrier and the subcarriers generated by two similar plant sensors, tuned to operate at different central frequencies, during the scatter radio communication with the reader, for the voltage levels produced by the plant of −600 mV and +600 mV, respectively.

by these two plant sensors, for the entire range of the plant signal voltage levels, were set at 868.016–868.021 kHz and 868.023–868.030 kHz, respectively, in order to ensure that the bandwidths occupied by the individual plant sensors do not overlap (and hence simultaneous transmission is not compromised). The tuning of these frequency bands has been implemented by appropriately adjusting the value of V_{ref} in (4), which has been applied in each plant sensor.

Two alternative bistatic topology configurations were experimentally investigated, with the distances between the reader and the wireless plant sensor node (i.e., distance d_{r-n} in Fig. 2) equal to 14.6 m and 19.3 m, respectively, while the wireless plant sensor node-to-emitter distances (i.e., distance d_{n-e} in Fig. 2) were 13.3 m and 16.4 m, respectively. The resulting values of the mean SNR as well as the root mean square (rms) and mean absolute error (MAE) are presented in Table II. As experimentally demonstrated in [36], by applying denoising filtering in the reader software, an operational distance d_{r-n} of about 96 m as well as a distance d_{n-e} equal to 40 m can be achieved, with the sensor operation duration t_{ON} on the order of 100 ms. The experimental results presented above demonstrate that the backscattering communication principle, which has been employed in the design of the proposed wireless plant sensor, enables to achieve a relatively long communication distance with minimum power supply requirements.

Fig. 6 shows the time series of the *(unprocessed)* avocado plant EP signal measurements, acquired by the proposed self-powered wireless plant sensor and transmitted to the SDR-based reader during eight consecutive days. The proposed wireless plant sensor was supplied power by the energy harvested from the avocado plant, according to Section III-A, during that experimental process. Environmental humidity, solar irradiance, and temperature at the same location of the plant are also depicted. The Action Potential signals generated shortly after the irrigation events are also illustrated, indicating that plant depolarization [17] takes place for a few minutes after the irrigation event. Furthermore, significant plant response is exhibited during the incidence of solar irradiation. It is observed that both the irrigation events and the ambient solar irradiation conditions are fully correlated with the unprocessed EP plant signal.

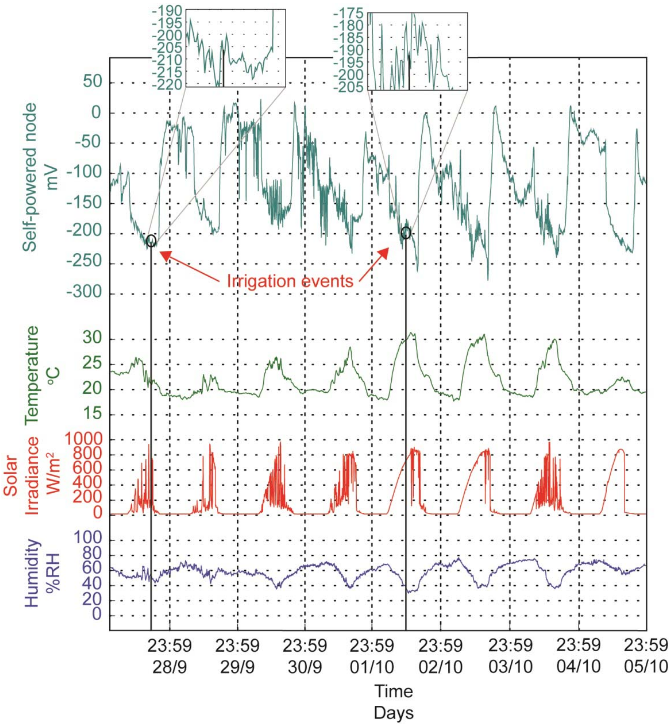


Fig. 6. Experimental measurements of the electrophysiological signal generated by an avocado plant during the days September 28–October 5, 2014, which have been received by the reader through the backscatter communication link after having been acquired by the proposed self-powered wireless sensor; the corresponding meteorological conditions are also depicted.

Even though, as demonstrated in Fig. 6, environmental conditions and irrigation times were visible with the bare eye at the plant EP signal, further processing was established to reduce noise via soft undecimated wavelet thresholding using a threshold selection rule based on Stein's unbiased estimate of risk [41]. The plant signals were normalized to [0, 1] and NMF was applied to the recorded signal matrix $\boldsymbol{X}$, as described in Section III-D, in order to extract a single component present in all recorded EP signals.

As analyzed in Section III, the proposed wireless plant sensor is batteryless and has been designed to operate fully autonomously by harvesting the plant-generated energy. However, in order to verify that the implemented plant energy harvesting scheme described in Section III-A does not degrade the signal acquisition and wireless transmission capabilities of the proposed wireless plant sensor, battery-operated versions of the proposed design were also constructed. The NMF analysis of the EP signals acquired from two avocado plants during four consecutive days, where batteries have been employed for supplying power to the proposed wireless sensors instead of the plant energy harvesters, is presented in Fig. 7. The two subfigures of Fig. 7 (left) display the recorded EP signals from the two avocado plants. The signals are denoised to remove sensor noise. Consequently, the two denoised plant EP signals are presented as inputs to the NMF algorithm. The NMF algorithm has been configured to extract a single common component from the two input EP signals using ALS optimization. The first extracted component is shown in Fig. 7 (top right). This component shows close correlation with the actual solar irradiance pattern recorded by an actual

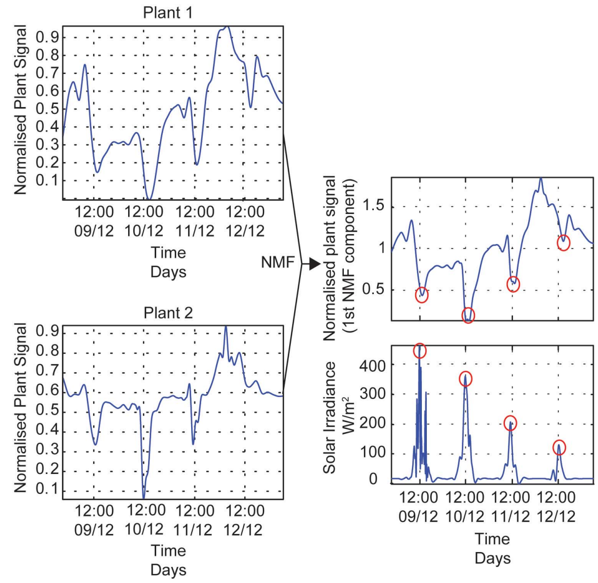


Fig. 7. NMF analysis of EP signals acquired from two avocado plants using the proposed wireless sensors with battery-based power supply in a four-day scenario.

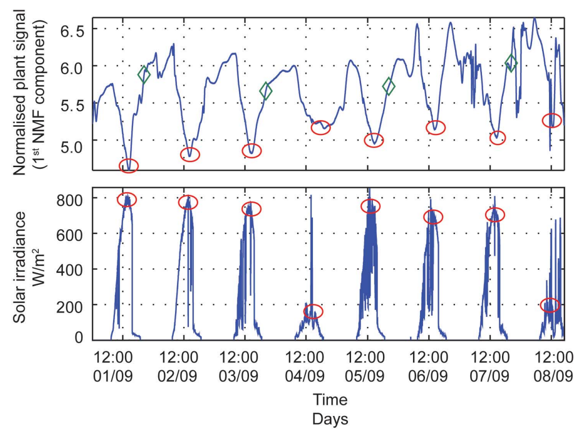


Fig. 8. NMF analysis of EP signals acquired from nine avocado plants using the proposed wireless sensors with battery-based power supply in a seven-day scenario.

solar irradiance sensor [see Fig. 7 (bottom right)]. This close correlation clearly demonstrates that both plants can sense and respond to daylight. Thus, their EP signals are influenced by solar activity.

A nine-plant seven-day scenario is shown in Fig. 8, with battery-operated sensors, where the first extracted NMF component closely follows the solar irradiance waveform in terms of temporal accuracy. The first NMF component from nine-plant electrical signals [see Fig. 8 (top)] shows a similar high correlation with solar irradiance [see Fig. 8 (bottom)]. The green diamond markers in Fig. 8 (top) denote manual irrigation times. It appears that manual irrigation coincides with the changes of positive slope in this first NMF component. The location of the deeps in the NMF signal indicates the existence of corresponding solar irradiance peaks. The depth of each NMF deep corresponds to the respective light intensity measurement. The fourth day with smaller solar intensity can be inferred from the NMF

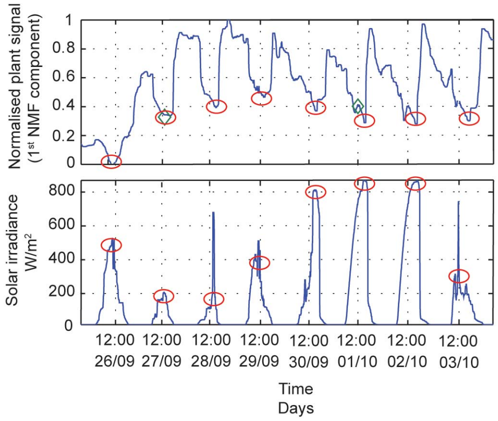


Fig. 9. NMF analysis of the EP signal acquired from one avocado plant using the proposed wireless sensor in self-powered mode of operation (i.e., harvesting energy from the plant) in an eight-day scenario.

component. It is noteworthy that the intensity of the deeps in the extracted component corresponds to the intensity of the peaks in the solar irradiance waveform. In other words, the plant wirelessly transmitted and processed EP signal offers light intensity information, i.e., the plant is the light sensor. The same experiment demonstrates another preliminary finding, concerning plant irrigation. It appears that manual plant watering times coincide and correlate with the changes of positive slope on the extracted component. This preliminary finding may provide hints for appropriate automated plant irrigation in the future by tracking the changes of positive slope in the NMF component. These findings may in turn imply that the plant network can sense its needs and communicate them to the outside world via the developed wireless sensors.

Fig. 9 presents the NMF analysis of the EP signal from one plant, which is plotted in Fig. 6, where the plant energy harvesting subsystem described in Section III-A has been used for supplying power to the signal conditioning and RF communication units of the proposed wireless plant sensor (i.e., the proposed wireless sensor is self-powered). The time instants at which the change of positive slope takes place due to irrigation events (marked as diamonds) are clearly denoted. Furthermore, it is observed that even though the sensor uses the energy harvested from the plant, its EP signal shows similarly a high correlation with solar irradiance, thus being in alignment with the findings described above.

V. Conclusion

The measurement of the biologic EP signals produced by plants has been the subject of scientific research in the past, since it is critical to monitoring their response to external stimuli, such as irrigation events and environmental light. However, data acquisition of a massive amount of EP signals (from one or multiple plants, e.g., in precision agriculture applications and plant physiology) is hindered by the existing battery-operated instrumentation technology and the increased associated monetary cost.

In this paper, a self-powered batteryless EP instrumentation apparatus has been proposed for the first time in the existing research literature that harvests near-maximum energy from the plant itself and transmits the EP signal with a single switch, based on inherently low-cost and low-power bistatic scatter radio principles. The hardware design of the wireless plant sensor presented in this paper is directly applicable for monitoring any plant type. In contrast to the existing instrumentation technology for plant monitoring, the proposed ultralow-cost batteryless design enables the formation of large-scale and fully autonomous WSNs for monitoring multiple plants of the same or different types over a broad area. Fully functional experimental prototypes of the proposed self-powered wireless sensor node have been developed, which feature a total power consumption of 10.6 μW and can accommodate simultaneous operation of multiple plants. The ability of the proposed wireless plant sensor to achieve a fully autonomous operation by harvesting the energy generated by the plant itself has been confirmed experimentally under real-life operating conditions using an avocado plant as a reference. Furthermore, the EP signals, experimentally acquired by the proposed wireless sensors from multiple avocado plants, were processed using NMF, revealing a strong correlation with environmental light irradiation intensity and plant watering. Thus, it has been experimentally demonstrated in this paper for the first time in the existing research literature as to how an avocado plant can be converted to an ultralow-cost batteryless wireless sensor of environmental light and irrigation perceived by the plant itself instead of being estimated through sensors installed at its surrounding environment.

Future work includes the conduction of long-term experimental studies for investigating the power production characteristics of various plant types and their correlation with the plant physiology, as well as the environmental and soil conditions, which has not yet been investigated by the scientific research. The instrumentation approach presented in this paper is a first but solid step toward the conduction of large-scale electrophysiology studies for various plant types in the future regarding the underlying reactions to environmental conditions and external stimuli. The scalability and fully autonomous features of the proposed wireless plant sensor will be exploited for that purpose. In this way, the proposed plant-as-sensor-and-battery idea will be further elevated, with potential applications of significant socioeconomic impact in ecology, plant biology, as well as precision agriculture.

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