

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

Christos Konstantopoulos, Eftichios Koutroulis, *Senior Member, IEEE*, Nikolaos Mitianoudis, *Senior Member, IEEE* and Aggelos Bletsas, *Senior Member, IEEE*

Abstract — Electric Potential (EP) signals are produced in plants through intracellular processes, in response to external stimuli (e.g. watering, mechanical stress, light, 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, battery-less 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. Also, EP signals experimentally acquired by the proposed wireless sensor from multiple plants, have been processed using Non-negative Matrix Factorization (NMF), demonstrating strong correlation with environmental light irradiation intensity and plant watering. The proposed low-cost, battery-less “plant-as-sensor-and-battery” instrumentation approach is a first but solid step towards large-scale electrophysiology studies of important socioeconomic impact in ecology, plant biology, as well as precision agriculture.

Index terms — Wireless Sensor Network, energy harvesting, plant, scatter radio.

I. INTRODUCTION

Constant monitoring of micro-climate 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.

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 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, interface with a client application software) through a GSM/GPRS-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, 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 (a.k.a. parastichies), with speeds on the order of a few cm/min, 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 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 by 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) electric potential (EP) mechanism that could elevate the “plant-as-sensor” itself idea. However, wireless transmission of a massive amount of electric potential signals (from one or multiple plants) is hindered by existing, *battery-operated* wireless technology

C. Konstantopoulos, E. Koutroulis and A. Bletsas are with School of Electronic and Computer Engineering, Technical University of Crete (TUC), Greece, GR-73100. N. Mitianoudis is with Department of Electrical & Computer Engineering, Democritus University of Thrace. Email: {ckons89@gmail.com, efkout@electronics.tuc.gr, nmitiano@ee.duth.gr, aggelos@telecom.tuc.gr}.

and increased, associated monetary cost of conventional Marconi-type radios (e.g. [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.

Battery-less telemetry designs have exploited solar, magnetic (e.g. [19]), kinetic (e.g. [20], [21]), Radio Frequency (RF - e.g. [22]-[25]), thermoelectric (e.g. [26], [27]) and wind (e.g. [28], [29]) energy harvesting techniques, combination of them (e.g. [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 tracking (MPPT) principles. An additional hindrance of employing these forms of energy production schemes in precision agriculture applications, where a large number of sensing nodes is 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, 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, how an Avocado (*Persea Americana*) plant can be converted to a battery-less wireless sensor of environmental light and irrigation, harvesting and storing energy from itself. For that purpose, the design of a self-powered, battery-less EP wireless sensor is presented in this paper, which: (i) measures the EP signal generated by the plant under monitoring, (ii) transmits the EP signal with a single switch, based on inherently low-cost and low-power bistatic scatter radio principles and (iii) harvests near-maximum energy from the plant itself for power-supplying the wireless plant sensor electronic circuits, thus achieving 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 (e.g. [1]-[7], [21], [28]-[29], [32]-[33], [35]). **Instead, this work employs a voltage-controlled**

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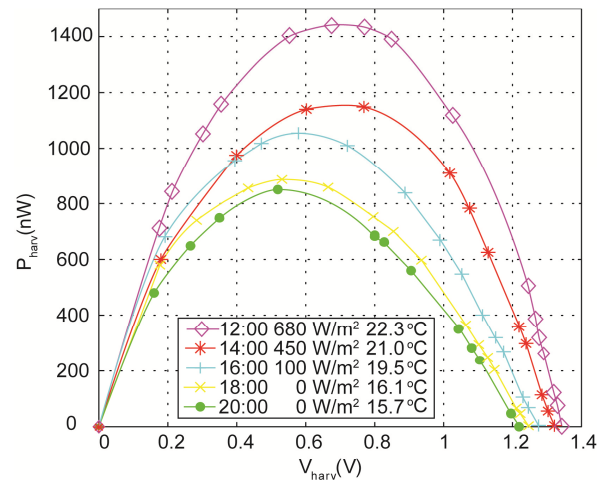


Fig. 1. The power-voltage characteristics of the electrical signal generated by an Avocado tree during a day and the corresponding values of solar irradiation and ambient temperature.

oscillator 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 receiver, the EP signal can be recomposed with frequency-based, maximum likelihood (i.e. periodogram) demodulation techniques.

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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, outdoor fields etc.) 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 monitoring¹. 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.

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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

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

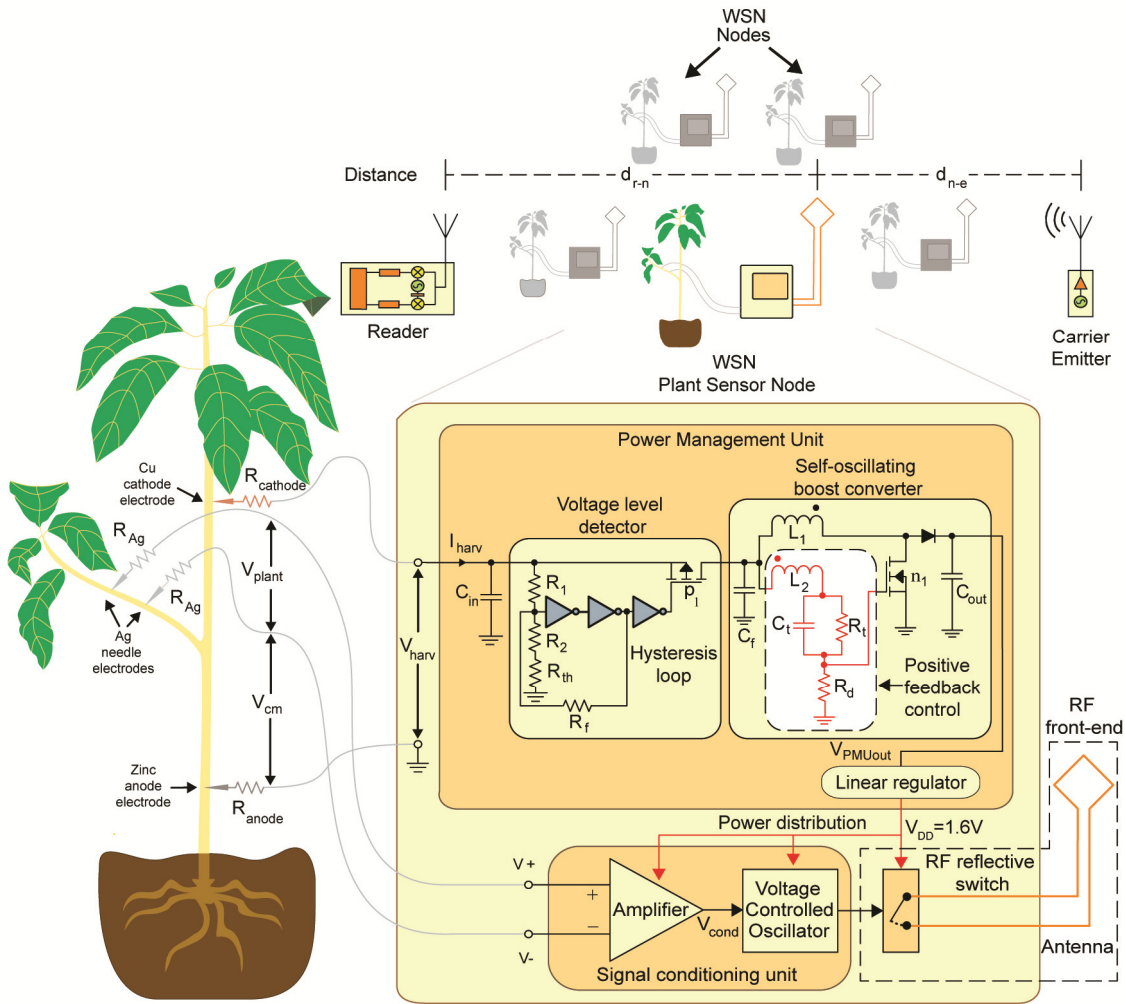


Fig. 2. A schematic diagram of the proposed self-powered wireless sensor, as well as the experimental topology.

different types of plants. The proposed low-cost, battery-less and wireless approach offers proof-of-concept for the “plant-as-sensor-and-battery” idea. Additionally, 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, conclusions are offered 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 power-voltage characteristic was not explored. Fig. 1 illustrates the experimentally measured power-voltage characteristics of an Avocado plant (*Persea Americana*) during a day. In this work, Zinc anode alloy in combination with a copper cathode were 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 maximum power point (MPP), where plant-generated power is maximized. The power harvested from the plant is equal to $P_{harv} = I_{harv} \cdot V_{harv}$, 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 of 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. Power capacity of such figure was exploited in the overall design of the proposed wireless sensor, as explained next.

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, consisting of the power management, signal-conditioning and RF communication units. The power management unit harvests the plant-generated energy for power-supplying 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 § II, a very low amount of power is produced by the plant. In order to exploit it for power-supplying 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} progressively rise; after sufficient energy has been accumulated in C_{in} , rising the voltage across its terminals to the appropriate level, the power management unit is re-activated, 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 iteratively repeated, determining the duty-cycle, D , of the proposed wireless sensor operation, which is defined as follows:

$$D = \frac{t_{on}}{T_{op}} = \frac{t_{on}}{t_{on} + t_{off}} \quad (1)$$

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, the daily and seasonal variations of plant physiology etc.) 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. Also, by designing the DC-DC power converter to operate in the DC input voltage range of 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 ultra low input power. The CMOS inverters are directly power-supplied 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 (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 pre-set 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_f 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 power-supplied 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}

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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 towards the power converter.

The sensitivity of the upper and lower thresholds with temperature is compensated by integrating a negative temperature coefficient (NTC) thermistor (R_{th} in Fig. 2) and appropriate selection of 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, 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 § 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 voltage-controlled oscillator (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:

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

where:

$$V_{plant} = V_+ - V_- \quad (3)$$

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

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

As will be demonstrated in the experimental results, 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 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 [i.e. (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, software-defined radio (SDR) receiver, which comprises the data-acquisition unit of the WSN (i.e. 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 range of switching frequencies across different plants.

In the conventional, Marconi-type radio technology (e.g. Bluetooth, ZigBee, WiFi etc.), 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 only passively reflects 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 to 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 the plant sensors modulation-frequency drift with temperature. For that purpose, a 3rd 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

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sensor measurements. Specifically, detection of the modulated EP signal start was performed with continuous energy calculation of sample sequences having 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 X . Each row of matrix X contains a time-series of EP signal measurements from a different plant. In order to identify common factors that influence the electrical conditioning of all plants, Non-negative Matrix Factorization (NMF) [42], [43] was exploited, i.e. finding positive semi-definite matrices V , W corresponding (qualitatively) to the components and (quantitatively) to their weight, respectively, such that $X= WV$. Solution to this problem is provided via minimizing a divergence function between X and the product $X= WV$, under the positive-semi-definite (non-negative) 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 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 ultra low consumption and ultra low input current bias that is crucial for the signal condition of the weak plant signals. Additionally, 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 comprises also a TS3002 timer, configured to operate as a VCO. The RF unit consists of the low power single ADG902 wideband CMOS switch, connected to the an omnidirectional monopole antenna that 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 μ W, 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 § III.C, this power consumption remains constant during operation of the proposed wireless



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

plant sensor. Such an ultra low power consumption has been achieved by: (i) using integrated circuits with ultra-low power supply requirements (e.g. operational amplifiers, timer etc.) for implementing the proposed wireless sensor, and (ii) employing the backscattering principle for implementing the RF front-end, according to § III.C. The total cost for constructing the proposed plant EP sensor in quantities of 100 pieces, is approximately 8.70 Euros.

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, values of $R_{th} = 5.6 \text{ M}\Omega$, $R_I = 5.8 \text{ M}\Omega$ and $R_2 = 3.3 \text{ M}\Omega$ were employed (see Fig. 2), resulting in variation of V_H and V_L in the ranges of 703-635 mV and 553-544 mV, respectively, for a 2.0-29.0 $^{\circ}$ 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 of 2.0 - 29.0 $^{\circ}$ 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 core-less transformer with $L_1 = 13 \text{ }\mu\text{H}$, $L_2 = 12.3 \text{ }\mu\text{H}$. The values of R_t, C_t, 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

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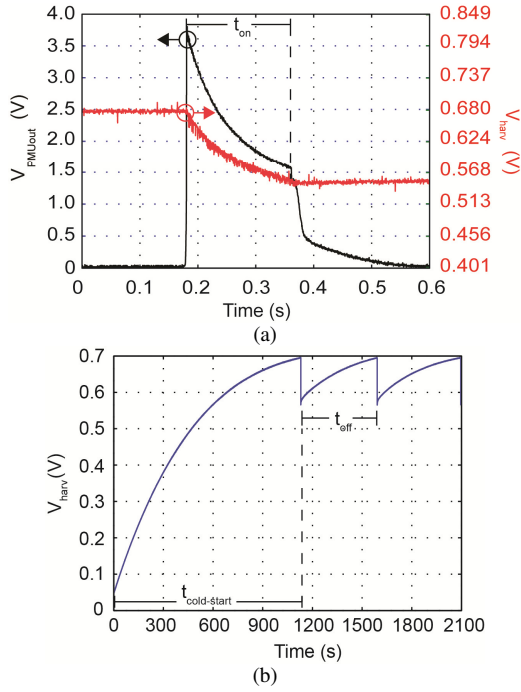


Fig. 4. a) The unregulated output voltage of the DC-DC Boost-type power converter during operation of the power management unit and b) The duty cycle operation of the proposed self-powered wireless sensor, where the input voltage fluctuates between the V_H and V_L thresholds.

electric resistance of anode and cathode harvesting electrodes and wires (R_{anode} and $R_{cathode}$ in Fig. 2) were measured at 0.066Ω and 0.057Ω , respectively.

An Avocado plant has been chosen as a reference in this work 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 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 power-supplied by energy harvested from the Avocado plant during that experimental process, as analyzed in § III.A. Since the power converter operates without an embedded regulation capability, an initial overshoot arises. Fig. 4(b) illustrates the fluctuation of the DC input capacitor voltage (i.e. power management unit), depicting time $t_{cold-start}$ needed for the overall system to start operating the first time (i.e. from cold start). After the cold start time $t_{cold-start}$, spanning about 1130 sec, the input capacitor voltage fluctuates between the V_H and V_L thresholds. During the t_{off} time interval, capacitor C_{in} is charged towards the V_H level by accumulating the plant-generated electrical energy. This procedure restarts after the capacitor has been discharged to

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

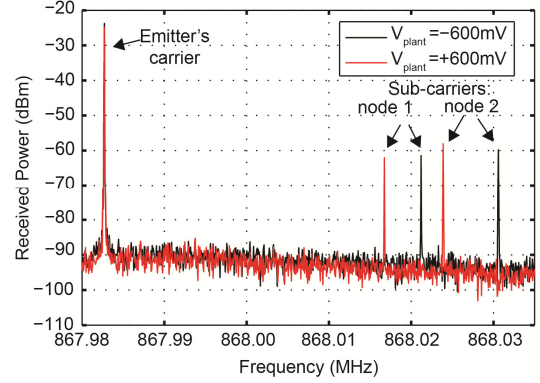


Fig. 5. The RF emitter carrier and the sub-carriers generated by two similar plant sensors, tuned to operate at different central frequencies, during the scatter radio communication with the reader, for voltage levels produced by the plant of -600 mV and $+600 \text{ mV}$, respectively.

the predefined level (i.e. V_L). The duty cycle value as calculated in (1), indicated by Fig. 4(a) and (b), is $3.80 \cdot 10^{-4}$.

The power conversion efficiency of the power management unit is 1.1% operating at $V_{harv} = 589 \text{ mV}$. 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 illustrates 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 $+600 \text{ mV}$, respectively. The gain G_1 in (2) was set at $67.34 \cdot 10^3$ and $74.87 \cdot 10^3$, respectively, at these two wireless sensors, while $G_2 = 0.1$ was set at both sensors. Thus, the frequency bands occupied by these two plant sensors, for the entire range of the plant signal voltage levels, were set at $868.016\text{-}868.021 \text{ kHz}$ and $868.023\text{-}868.030 \text{ kHz}$, 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 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

TABLE II: SNR AND MEASUREMENT ERROR FOR TWO ALTERNATIVE BISTATIC TOPOLOGIES.

Topology		SNR	Error	
d_{r-n} (m)	d_{n-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

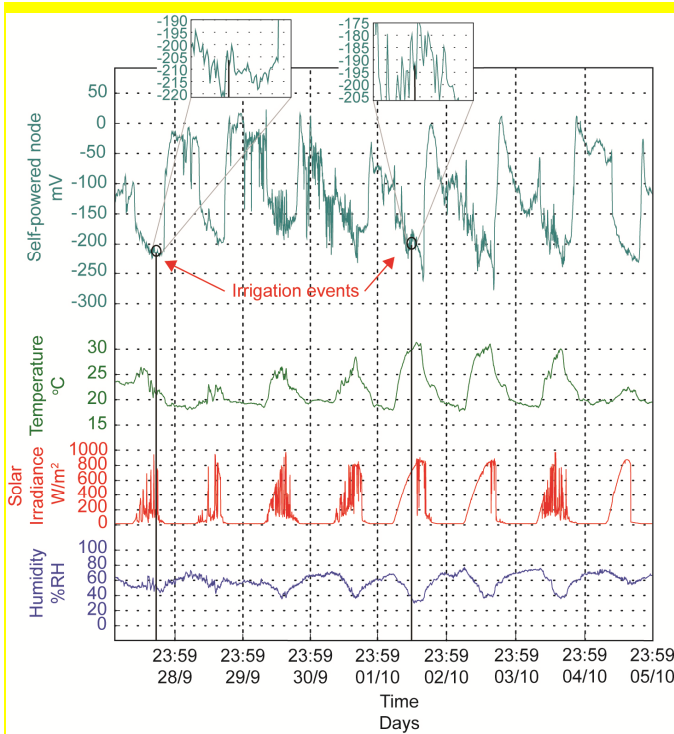


Fig. 6. Experimental measurements of the electro-physiological signal generated by an Avocado plant during the days 28/9/2014 - 5/10/2014, which have been received by the reader through the backscatter communication link after having been acquired by the proposed self-powered wireless sensor; the corresponding meteorological conditions are also depicted.

Fig. 2) were 13.3 m and 16.4 m, respectively. The resulting values of the mean Signal-to-Noise Ratio (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 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 illustrates 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 power-supplied by energy

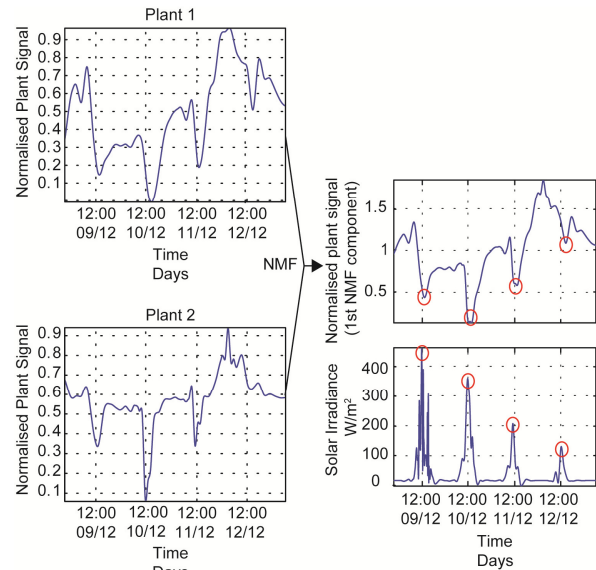


Fig. 7. The NMF analysis of EP signals acquired from two Avocado plants using the proposed wireless sensors with battery-based power supply, in a four-day scenario.

harvested from the Avocado plant, according to § III.A, during that experimental process. Environmental humidity, solar irradiance and temperature at the same location of the plant are also depicted. The AP 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 incidence of solar irradiation. It is observed that both the irrigation events, as well as the ambient solar irradiation conditions, are fully correlated with the unprocessed EP plant signal.

Even though that as demonstrated in Fig. 6, environmental conditions and irrigation times were visible with 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 normalised to [0,1] and NMF was applied to the recorded signal matrix X , as described in Section III.D, in order to extract a single component present in all recorded EP signals.

As analyzed in § III, the proposed wireless plant sensor is battery-less 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 § 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 power-supplying the proposed wireless sensors instead of the plant energy harvesters, is presented in Fig. 7. The two subfigures of Fig. 7 on the left display the recorded EP signals from the two Avocado plants. The signals are de-noised to

2.6

AE.2, 2.2, 2.3 & 2.4

AE.2, 2.2, 2.3 & 2.4

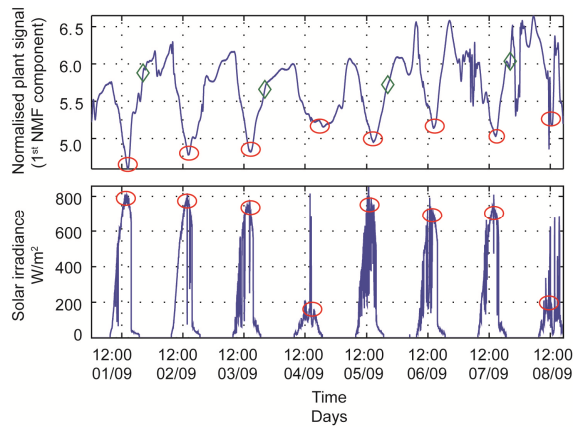


Fig. 8. The NMF analysis of EP signals acquired from nine Avocado plants using the proposed wireless sensors with battery-based power supply, in a seven-day scenario.

remove sensor noise. Consequently, the two de-noised 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 signal using ALS optimization. The first extracted component is depicted in Fig. 7 (top right). This component shows close correlation with the actual solar irradiance pattern recorded by an actual solar irradiance sensor (Fig. 7 - bottom right). This close correlation demonstrates clearly that both plants can sense and respond to daylight. Thus, their EP signals are influenced by solar activity.

A 9-plant, 7-day scenario is depicted in Fig. 8, with battery-operated sensors, where the first extracted NMF component follows closely the solar irradiance waveform in terms of temporal accuracy. The first NMF component from nine plant electrical signals (Fig. 8 - top) shows similar high correlation with solar irradiance (Fig. 8 - bottom). The green diamond markers denote manual irrigation times. It appears that manual irrigation coincides with changes of positive slope in this first NMF component. Location of the "deeps" in the NMF signal indicates 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 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 changes of positive slope on the extracted component. This preliminary finding may provide hints for appropriate automated plant irrigation in the future, by tracking 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

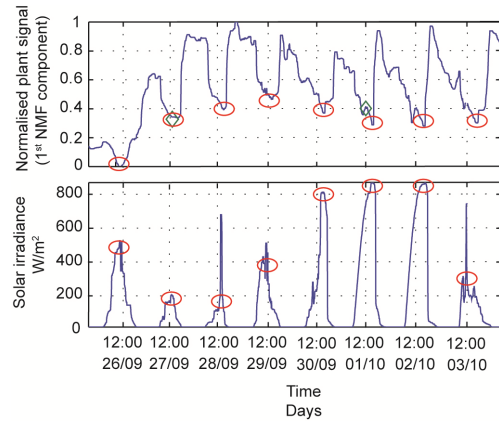


Fig. 9. The NMF analysis of the EP signal acquired from one Avocado plant using the proposed wireless sensor in self-powered mode of operation (i.e. harvesting energy from the plant), in an eight-day scenario.

harvesting subsystem described in § III.A has been used for power-supplying 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 that 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 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. CONCLUSIONS

The measurement of the biologic EP signals produced by plants has been the subject of scientific research in the past, since it is critical for 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, plant physiology studies etc.), is hindered by existing, battery-operated instrumentation technology and increased, associated monetary cost.

In this paper, a self-powered, battery-less 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 ultra-low cost, battery-less 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 μ W 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

AE.2, 2.3 & 2.9
 2.9
 2.2, 2.4 & 2.9
 AE.2, & 2.9

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 non-negative matrix factorization (NMF), revealing 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 how an Avocado plant can be converted to an ultra-low cost, battery-less 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 towards 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 full-autonomy 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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