Ambient FM Backscattering for Smart Agricultural Monitoring

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***Abstract*—Nowadays the measurement of moisture level in plants is critical for agriculture. One way to detect this is to measure the temperature difference between the leaf and the air. This paper introduces a novel wireless leaf temperature sensor that utilizes ambient FM backscattering for smart agricultural applications. The sensor is based on an ultra low power micro-controller, a sensor board and a RF front-end for wireless communication. The sensor communicates using backscatter radio principles on ambient FM station signals using AM modulation with FM0 encoding. The prototype featured an effective operation up to ranges of 0.5 m by backscattering sensor information at 50 bps and 500 bps using an ambient FM radio signal inside a laboratory setup. A high percentage of bits was clearly visible up to 2 m at 50 bps.**

***Index Terms*—Ambient Backscattering, Backscatter Communication, Internet of Things, RFID, Sensors**

I. Introduction

Over the last decade, the prediction of the impact of the climate change on agriculture applications (watering, tackling plant diseases etc.), requires a cheap, low-maintenance, effective, wireless telemetry of various environmental parameters, such as soil moisture, humidity and temperature. Various Wireless Sensor Networks (WSNs) topologies have been deployed for the wireless monitoring of those environmental parameters, at specific locations of crop fields. Sensing these parameters over broad areas offers the capability to perform a precise analysis of the generated micro-climate conditions.

Detecting the temperature difference between the leaves and the air is a well proven monitoring practice, especially to obtain reliable and correct measurements of water stress. The information should be captured directly from the plant and not form the air or the soil as only the plant responds at the same time to the soil conditions and the weather. Exporting real-time measurements of leaf-air temperature difference can inform the farmer, when the plant is thirsty from information obtained from the plant itself. Recent work based on this idea [1], shows that the temperature difference (T_{leaf}- T_{air}), is directly related with the meteorological event of rainfalls.

Traditional WSNs (e.g. ZigBee) are limited by high cost and high power consumption. Alternatively, sensor tags based on backscatter radio principles have appeared recently in order to address the above limitations [2], [3]. In [2] a low cost RFID based sensing platform was proposed. The sensor is battery-free and can operate using RF power, transmitted from a RFID reader. In [3] each tag has the ability to measure and send soil moisture measurements to a Software Defined Radio (SDR). The sensor network of [3] has been deployed with low power and ultra low cost. Traditionally in backscatter communication systems the reader is used to provide the RF power for power supply and communication. In order to take advantage of existing RF signal transmissions, ambient backscattering was proposed in [4] and digital TV station signals were used for power supply and device-to-device communication.

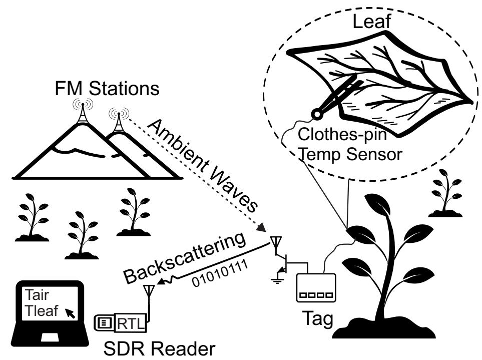

Fig. 1. Backscatter communication using ambient Frequency Modulated (FM) signals. Plant-leaf differential temperature (T_{leaf}- T_{air}) is measured by the tag and is sent back to a low cost RTL-SDR reader. Information is modulated on an ambient FM station signal using AM modulation and FM0 encoding.

In this work we develop a novel tag for leaf temperature measurements which uses for the first time ambient backscattering over analog modulated (FM) signals. The tag, shown in Fig. 1, reflects ambient RF signals from nearby FM stations in order to communicate with the reader. By using ambient signals for backscattering the reader architecture is simplified and its power consumption is reduced dramatically since it does not need a transmitter but only a receiver circuit. Our work is different from [4] in that we demonstrate ambient backscattering over analog modulated signals (ambient FM) and not wideband digitally modulated signals (ambient DTV), thus extending the concept of ambient backscattering over analog modulation. In addition, we perform matched filtering following reception of the backscattered signal envelope, optimizing the correct receive symbol probability. The sensing tag topology consists of a micro-controller (MCU) for processing, a sensor board for the plant sensing and a RF front-end consisting of a commercial switch and an antenna for the communication.

II. Backscatter principles

Backscatter modulation is based on a multiple-antenna-load system reflection coefficient: $\Gamma_{\text{i}} = (Z_{\text{i}} - Z_{\text{a}}^{*})/(Z_{\text{i}} + Z_{\text{a}})$, with $\text{i} = 1, 2, ...$ and Z_{a} is the antenna impedance. Typically, in RFID applications, in order to implemente a binary communication, a RF switch alternates the antenna termination load between two values (Z_1 and Z_2). The modulation is resulting from the change of Γ_{i} over time [5] and the phase difference

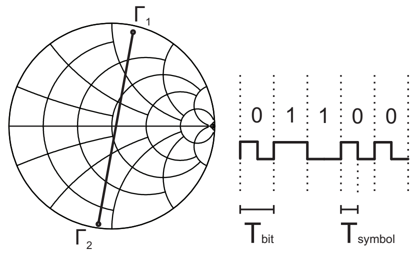

Fig. 2. Left: Antenna S_{11} Parameters in Smith Chart. Different antenna termination loads offer different reflection coefficients that modulate the FM station signal with different amplitude. Right: FM0 encoding technique.

of Γ_1 and Γ_2 in Smith Chart diagram, should be 180 degrees (Fig. 2, left) for the optimal backscatter performance. Typically a tag communicates with a reader by time modulating the reflected waves due to the incident continuous wave (CW) carrier, that is supplied by the reader. Instead, in this paper the incident CW carrier is an ambient FM station analog signal.

III. Wireless Sensor Node Design

The of the proof-of-concept sensing tag, based on a MSP-EXP430FR5969 development kit (Fig. 3), generates the pulses that control the RF switch, so that amplitude modulation (AM) with FM0 encoding can be implemented via backscatter radio. The MCU was programmed at 1 MHz clock with active mode current consumption (I_{DD}), 126 μA at 2.3 V (290 μW). For the temperature data acquisition, the embedded Analog to Digital Converter (ADC) is used. The sensor board consists of two high precision, ($\pm 0.1°$C) analog temperature sensors LMT70A (I_{DD} : 10 μA at 2.3 V) in a "clothes-pin" prototype in order to be easily fixed on the leaf (Fig. 3(a)). The first sensor on top, measures the air temperature (T_{air}) and the second under the leaf surface, measures the leaf temperature (T_{leaf}). The RF front-end consists of a wire dipole antenna to transmit/receive for FM station signals and the single-pole, single-throw (SPST) RF switch ADG902 (Fig. 3(b)). Each arm of the dipole is 1.45 m long to resonate within the FM band. The sensor board and the RF front-end prototypes were fabricated using inkjet-printed technology on commercial photo paper. Finally all parts of tag were powered by a 0.1 F super capacitor which was embedded on MCU Launchpad. Energy harvesting technologies can be used to charge the super capacitor, such as for example solar or RF energy harvesting [6]. Utilizing the embedded Real Time Clock (RTC) and the sleep mode of MCU the duty cycle of the tag (active mode percentage of time) can be reduced, thus reducing accordingly its average power consumption.

IV. Communication & Reader

Changing the RF switch between "on" and "off" states, can easily create a binary amplitude modulated signal by backscattering the ambient FM station signals impinging on the dipole antenna. The proposed work employed the low-consuming-power FM0 encoding and AM modulation. The switch state changes at the beginning and the end of every bit ("0" or "1") but only bit "0" has an additional state change in the middle as shown in Fig. 2 (right). The period of symbol (T_{s}) is the period of bit (T_{bit}) divided by two while the reflected signal has a bit rate of $1/T_{\mathrm{bit}}$ bits per second (bps).

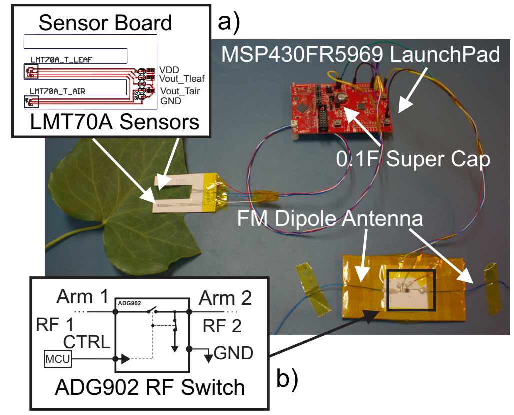

Fig. 3. The sensor node/tag consists of a MSP430 development board, a leaf "Clothes-pin" sensor board (a) and a RF front-end (switch and antenna) (b). The sensor board and the RF front-end prototypes were inkjet-printed on photo paper substrate. The tag was power supplied by a super capacitor.

The tag sends a data packet to the reader which consists of the preamble (16 bits), for bit-level synchronization at the receiver, the tag-ID (5 bits), the sensor-ID (8 bits) and the sensor-data (16 bits) section. The sensor-ID section is utilized so that the tag can support more than one sensor and the sensor-data section contains the uncoded data from the "ID-respective" individual sensor only. A complete packet in time domain is depicted in Fig. 5(a). The receiver is a low cost RTL-SDR USB dongle. The SDR with R820T radio tuner, has a 8-bit ADC and a tuning frequency range, from 24 MHz to 1850 MHz. The dongle down-converts the received RF signal to baseband with a sampling rate up to 2.8 MS/s. It also provides in-phase (I) and quadrature (Q) interleaved samples, directly to MATLAB software for extra data processing.

The received signal contains a distorted version of the transmitted rectangular pulses (bits of FM0 encoding) and, in order to effectively detect them it is necessary to compute the envelope of the received I and Q baseband signals (absolute value). After computing the envelope, a digital matched filter consisting of a square pulse with duration T_{s} is used to obtain the received symbols. The matched filter maximizes the symbol detection probability.

V. Measurements

In order to test the proposed system, an indoor setup was deployed as shown in Fig. 4. The tag was programmed to send packets with the measured values of T_{air}. The distance between the sensing tag antenna and the reader antenna was chosen to be 50 cm. The duration of symbols (T_{s}) was set to 1 ms and 10 ms. The SDR reader was tuned to the Georgia Tech student FM radio station, 91.1 MHz whose frequency spectrum is depicted at the top right of Fig. 4. The sampling rate was fixed at 1 MS/s.

Fig. 5(a) shows the transmitted packet corresponding to a measurement of 965 mV from T_{air} sensor. The binary representation of 965 is: 0000001111000101 as depicted in the sensor-data section of the packet. Using the third order transfer

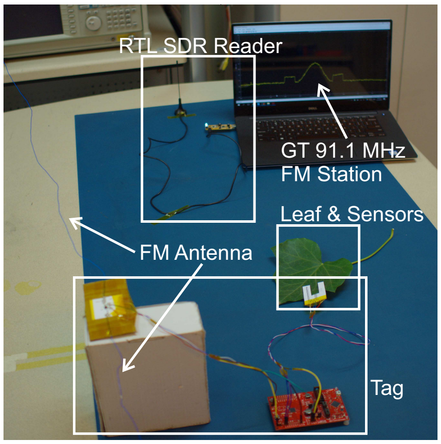

Fig. 4. Lab indoor implementation of sensing system. The tag antenna is placed 0.5 m away from the reader antenna for communication measurements.

function of LMT70A sensor [7], the output temperature was calculated to be 25.81°C. Figures 5(b)-(c), show the received packet for $T_{\text{symbol}} = 10$ ms and $T_{\text{symbol}} = 1$ ms, respectively. By comparing Fig. 5(a) and Fig. 5(b)-(c) one can see that the reader can correctly receive the transmitted packet at the correct sampling instants. In FM0 decoding, the reader distinguishes the "on" and "off" stages by observing voltage changes in the envelope magnitude. Measuring the duration between two changes, bit decoding can be achieved. There is a trade-off between bit rate and efficient filtering. If a higher bit rate is utilized (500 bps, Fig. 5(c)), there is less channel fluctuation but the matched filtering will not be able to remove the high frequency components of the ambient FM signal. On the other hand, for a lower bit rate (50 bps, Fig. 5(b)), a higher Signal-to-Noise ratio (SNR) will occur to the expense of channel fluctuation. Promising measurements at 2 meters show that a high percentage of bits is still clearly visible, while certain parts of the packet are significantly affected by the FM signal fluctuations. Future work will quantitatively assess the system performance loss at long tag-to-receiver distances and perform optimized detection of low-SNR signals.

For the above measurements, the tag power was supplied only from the super capacitor. For $T_{\text{symbol}} = 10$ ms, the super capacitor was charged initially at 3.63 V and after about 19.3 minutes of operation the voltage across it decreased to 1.8 V. The tag stopped to send packets at the minimum supply voltage of 1.8 V. During the packet transmission, the overall system current consumption was measured at 193 μA. The system was set to send a packet every 1.23 seconds.

VI. Conclusion

In this work, we introduce an ambient analog FM backscatter tag for agricultural purposes. The proposed tag combines low power operation and connectivity with a low cost RTL-SDR receiver. The communication was implemented by backscattering analog modulated ambient RF signals from FM stations. Ambient backscattering has the potential to be the next new primitive approach for extremely low power communication.

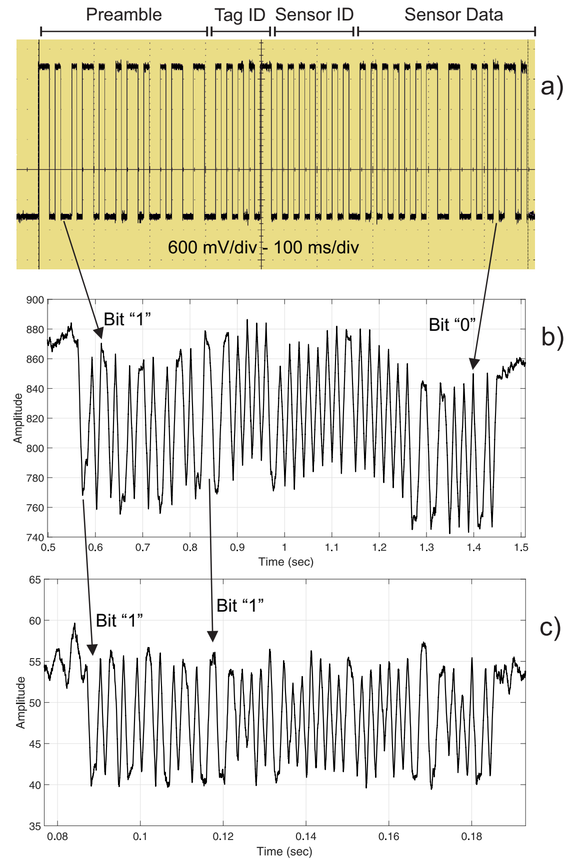

Fig. 5. Time domain backscatter packet signals, (a) oscilloscope measurement of transmitted rectangular pulses, (b) received packet pulses at $T_{\text{symbol}} = 10$ ms, (c) received packet pulses at $T_{\text{symbol}} = 1$ ms.

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