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# Innovative RFID Sensors for Internet of Things Applications

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*(Invited Paper)*

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**ABSTRACT** Radio-Frequency IDentification (RFID) devices and sensors are among the main innovations of the last years, with an enormous impact on the Internet of Things (IoT) physical communication layer as well as on logistics and robotics. The aim of the present paper is to review the main technologies available for RFID sensors, and to identify the corresponding state-of-the-art when these technologies are applied to realistic IoT scenarios. Firstly, the concepts of radio bascattering and harmonic bascattering are analyzed, highlighting the pros and cons of each approach. Then, state-of-the-art solutions are reported, and the performance of each of them are discussed, to provide an overview of the potential of RFID-based sensing in different scenarios.

**INDEX TERMS** Backscatter radio, harmonic RFID systems, NFC tags, RFID, RFID sensors.

## I. INTRODUCTION

The Internet of Things (IoT) scenario is driving a paradigm-shift in product design and implementation, since the electronics need to conform to the objects and not the contrary. Because of the emerging IoT applications, electronics are spreading in an increasing number of gadgets. Some of these devices, for example, aim at assisting human life, for instance, optimizing production processes, improving health assistance, and leading to a more efficient energy use, thus turning our familar everyday items into smart cooperative objects. The need to integrate IoT functions into common objects or even into human body, the so called wearable and implantable electronics, is imposing new design requirements, such as circuit conformability, object compatibility and low invasivity. Conversely, this massive deployment of electronic improved objects, many of which disposable, is generating environmental issues threatening the quality of human life and, ultimately, counteracting the original scope of the IoT and hindering its evolution, [1].

Short-range wireless communication of sensor data finds application in several fields ranging from the monitoring of biological parameters in medicine [2]–[7], to the measurements of mechanical quantities in industrial applications [8]–[11], and robot guidance [12]. In the last years several technologies have been developed to this purpose. Among them, the Radio-Frequency IDentification (RFID) concept [13] is emerging as a strategic approach, due to the convergence of several new ideas such as the RF-energy harvesting [14], [15], RF-carrier reuse, load modulation method, etc. The RF energy harvesting and the carrier reuse, for example, allow for battery-less RFID tags that can be disposable (batteries are very polluting devices), and able to operate without maintenance for long periods. From the point of view of materials, furthermore, organic [16]–[22], inkjet printed [23]–[28] and cellulose based electronics [29]–[33] are being developed and almost ready for the market. The advantage of cellulose is cost, which is significantly lower than that of standard Printed Circuit Boards (PCB) materials and, again, recyclability, low pollution and low environmental impact.

The concept of backscatter radio originates in 1945 when Leon Theremin developed an advanced passive listening device [34]. This system was a replica of the Great Seal of the United States and was used by the Soviet Union to spy on the US embassy in Moscow. The circuit consisted of a monopole antenna connected to a resonant cavity with a flexible sound-sensitive conductive membrane. The changes in the membrane modified the resonant frequency of the cavity and the antennas load. Thus, when the device was excited by an outside RF continuous wave (CW) signal, the antenna would reflect a signal modulated by the voices of those present in the room. In 1948, Harry Stockman reported a method to communicate by using reflections generated by mechanical devices, which included audio transfer over microwave frequencies. Modern tags such as RFIDs use similar modulated backscatter operating principles. These concepts gave rise to commercial applications for backscatter communication and Donald B. Harris was the first inventor to combine this technique with Wireless Power Transfer (WPT), by proposing a battery-free system for voice communication based on backscatter communication in 1960. From this date, RFID technology started to grow and has evolved into systems with different applications.

In backscatter communication, the tag reflects a radio signal transmitted by the reader, and modulates the reflection by controlling its own reflection coefficient [35]. The load modulator is a semiconductor device (like a diode or a transistor) that is able to synthesize two or more impedance levels. By changing the antenna impedance between these values, the tag can modulate the RF signal that is scattered back to the reader. This type of communication implies circuits that are different form those found in traditional wireless transceivers, and is fundamental for low-power implementations. The backscatter radio approach is found in conventinal chip-based RFID and Near-Field Communication (NFC) tags, like those reported in [36], [37]. The main advantages of such an approach are: i) the long-range capabilities and ii) the digital modulation of the signal that can contain complex codes and sensor data.

A different method has been recently introduced by [38]. Here the sensing principle is associated with the generation of an inter-modulation signal from a tag, the latter being illuminated by two waves at different frequencies. The advantage of this idea is that the tag response is generated at a perfectly known frequency, thus the presence or the absence of such a signal can be hardly equivocated. Similar techniques have been used in harmonic radar systems [39] and in one-bit frequency doubling tags [40]–[42]. In these systems the tag is interrogated at a certain frequency while it responds at an harmonic. The advantage of such a methodology is, as for the previous case, that the clutter from the surrounding environment can be removed (since it happens at the interrogation frequency, not at the harmonic one) and, as a consequence, the tag response is easily identified also in case of low-power interrogating signals.

In this paper the main types of RFID sensors are revised, pointing out their strengths and weak points, as well as illustrating the typical applications that falls into the IoT ecosystem. The discussion is focused on two main RFID tag categories, namely: i) off-the-shelf tags based on backscattering radio concept and ultra low-power Complementary Metal Oxide Semiconductors (CMOS) chips, and ii) harmonic tags. Each tag category is illustrated by several examples or case studies. The aim of such a discussion is to identify the state-of-the-art for the considered technologies when they are applied to realistic IoT scenarios.

## II. RFID-BASED SENSORS

An RFID system, in its most classic meaning, is composed of a series of tags and readers that allow the identification of tagged objects by using radio transmissions. Thanks to the fact that all the tags that are in the reading cone of a reader are activated simultaneously, this technology lends itself very well to the tracking of a production chain and for warehouse inventories. In this paper, we mainly want to highlight the sensing capabilities of this technology, especially when the goal is to create low-cost, energy-independent and possibly eco-compatible sensor networks. The frequency bands used by RFID technology are mainly 4: low frequency (LF) (125/134 kHz), high frequency (HF) (13.56 MHz), ultra high frequency (UHF) ($860 - 960$ MHz), and microwaves (2.4 GHz). The tags designed for the first two bands work in the near field and are based on an inductive coupling, while those designed for the last two exploit the transmission of an electromagnetic field through a radio link. As for the power, we can distinguish the tags among passive, semi-passive and active. Passive tags are those that exploit the signal generated by the reader during communication. Not having a transmitter on board, they are the most attractive in terms of size, weight and cost. Semi-passive tags use the same operating principle as passive ones, they are equipped with a battery used to power the microchip or auxiliary devices (sensors); they generally have a good amount of rewritable memory. The active tags are equipped with a battery which in this case is used to power the whole system which generally consists of a receiver, a transmitter and environmental sensors. Depending on the application, the most suitable frequency band and system type are selected [43].

### A. RADIO BACKSCATTERING

Passive and semi-passive RFID tags do not use a radio transmitter, they use modulation of the reflected power from the tag antenna. This way of communicating goes by the name of radio backscattering. In the backscatter communication, the tag reflects a radio signal transmitted by the reader, and modulates the reflection by controlling its own reflection coefficient, see Fig. 1. The load modulator is a semiconductor (p-i-n diode or transistor switch) that varies between two different impedances. By changing the antenna impedance between two values, the tag can modulate the RF signal that is scattered back to the reader. This kind of communication implies circuits that are different from those found in traditional wireless transceivers, and is fundamental for low-power implementations. Therefore, each sensor is equipped with a backscatter modulator working by simply switching on and off the impedance connected to the antenna port.

### B. HARMONIC BACKSCATTERING

Harmonic backscattering is the simplest form of radio backscattering. In harmonic systems, in fact, the transponder

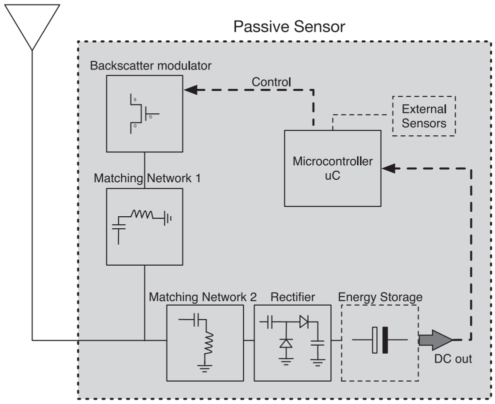



**FIGURE 1.** **The architecture of a radio backscattering system. From [44].**

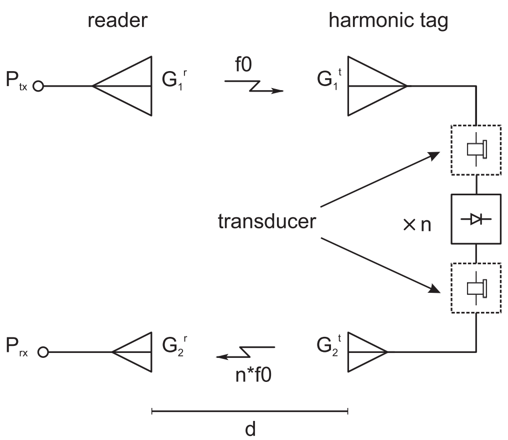



**FIGURE 2.** **Schematic diagram of a wireless sensing system based on the harmonic backscattering.**

converts the continuous-wave interrogating signal at the fundamental frequency $f_0$ to its second harmonic $2f_0$ [44]. This signal is then reflected back and it is detected by a receiver tuned to $2f_0$. The classical schematic diagram of a harmonic system is shown in Fig. 2. The harmonic generation is performed with a passive non-linear component, generally based on a low-barrier Schottky diode, called frequency doubler. A frequency doubler is characterized by its conversion loss $C_l$, defined as follows:

$$C_l = \frac{P_{load}^{2f_0}}{P_{avs}^{f_0}}, \tag{1}$$

where $P_{avs}^{f_0}$ is the available source power at $f_0$, and $P_{load}^{2f_0}$ is the output harmonic power delivered to the load. To extend the read-out distance of the system, the frequency doubler is generally designed to have a low $C_l$ for low available input power ($P_{avs}^{f_0} < -20\,\mathrm{dBm}$) [45], [46]. In the schematic in Fig. 2, the transponder has two separate antennas, one operating at $f_0$ and the other at $2f_0$; transponders characterized by a single dual-band antenna have also been investigated [46]. The eventual transducer can be placed before or after the frequency doubler. The information associated with the transducer is encoded in the second harmonic and it is recovered by the receiver.

Due to their operating principle, the read-out distance of harmonic tags is not limited by the minimum power at the input of the transponder, needed to switch on the transistor in traditional radio backscattering, but it is limited by the sensitivity of the receiver, i. e., by its capability to detect low-power signals. The power of the received second harmonic $P_{rx}^{(2f_0)}$ can be estimated as follows:

$$P_{rx}^{(2f_0)} = \frac{1}{4}\frac{P_{tx}^{(f_0)} G_1^r\, G_1^t\, G_2^t\, G_2^r}{Cl(par)}\left(\frac{\lambda_0}{4\pi d}\right)^4, \tag{2}$$

where $P_{tx}$ is the transmitted power at $f_0$, $d$ is the tag-to-reader distance, $G_i^j$ the specific antenna gain ($i = 1$ fundamental, $i = 2$ 2nd harmonic, $j = t$ tag, $j = r$ reader), and $Cl$ the overall conversion loss of the tag, which varies with the value assumed by the sensed parameter $par$, which can be temperature, humidity or strain, depending on the application.

Harmonic tags are not equipped with an identification number, therefore in case of multiple tags discriminating the single contributions among the responses of all others is more challenging. One possibility is to use a reader equipped with a highly directive antenna able to perform beam steering and illuminate a tag at a time. Some sensing architectures can be also tailored to allow for the contemporary presence of multiple tags, see Sec. III-D. Nevertheless, harmonic transponders are completely passive, which is a great advantage in the IoT framework, where a considerable amount of sensors are spread in the environment. Due to their robustness to radar clutter, harmonic-based transponders have been used for years in manifold scenarios, such as anti-collision automotive systems [47], insect tracking [48] and RECCO systems for avalanche victim detection [49], and are currently being investigated for sensing applications.

## III. APPLICATIONS IN RFID SENSING

In the following subsections, examples of wireless transponders for sensing applications, based on traditional radio backscattering and harmonic backscattering are illustrated, to show the potential of these emerging technologies.

### A. SMART BUTTON COMBINING NFC AND UHF RFID TRANSPONDERS FOR FASHION SUPPLY CHAIN TRACKING

In fashion, there is a strong need for transponders able not only to identify the single piece of clothing for inventory purposes, but also to provide additional information to the customers, such as its origin, instructions on washing, and so forth. While identification can be conveniently managed by UHF RFID systems, customers do not have access to UHF readers. Therefore, a single standard is not enough to satisfy all the requirements. At the same time, the developed transponders must be small, and must not impact on aesthetics. To this purpose, a dual standard smart button is here developed. The proposed smart button includes both an NFC and an UHF EPC Gen2 RFID transponder. The UHF transponder, based on the EPC Gen2 standard, is used for identification and anti-theft, while the NFC transponder allows the customer

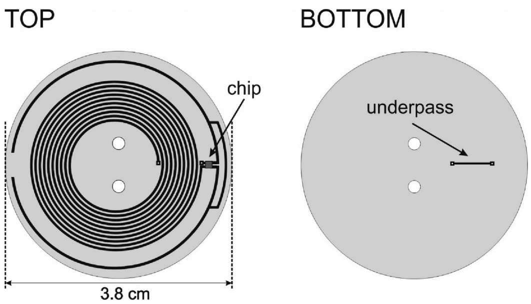



**FIGURE 3.** **Layout of the proposed dual-frequency smart button.**

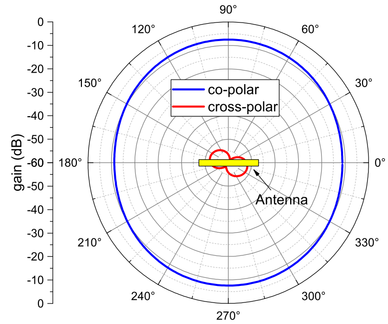



**FIGURE 4.** **Radiation pattern of the UHF antenna at 866 MHz.**

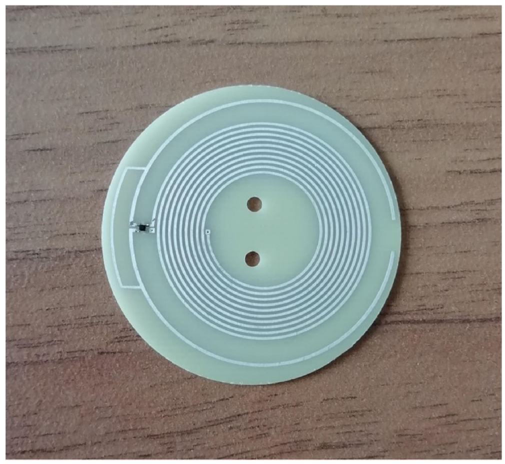


**FIGURE 5.** **Photo of the proposed dual-frequency smart button.**

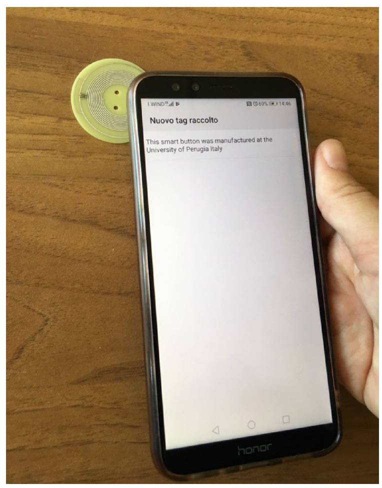



**FIGURE 6.** **Test of the NFC transponder. The tag is interrogated with an NFC reader integrated in a smatphone.**

to access information on the history of the purchased good with the NFC reader of their smartphones. Since both systems operate at relatively low frequencies (i.e., 13.56 MHz for the NFC and 866/915 MHz for the UHF RFID depending on the operating region), antennas tend to be quite cumbersome (half wavelength in the free space is equal to 17 cm at 866 MHz) [50]. In this work we pursued the challenging goal to accommodate the transponders of both systems in an area corresponding to a button, while maximizing their performance. The layout of the proposed smart button is shown in Fig. 3.

The transponders are based on a single dual-frequency chip, the EM4423 model from EM Microelectronic [51]. This chip provides the hardware needed by the NFC and the EPC Gen2 standards in a single die, which is accessible by two ports, one for the NFC and the other for the UHF transponder. The antennas are designed to achieve a good matching with the input impedances of the chip and are confined in a circular area corresponding to a flat coat button (diameter: 3.8 cm). An inductive spiral is used for the NFC and a folded dipole is used for the UHF tag. The UHF antenna, in particular, is placed on the outer annulus to maximize its length and surrounds the inductive spiral for NFC. The central area is left free to accommodate the button holes. According to the datasheet [52], the NFC port of the chip features an input impedance equal to a capacitance of 50 pF. Therefore, the antenna has to introduce an inductive contribution, corresponding to about 2.76 $\mu$H, able to resonate with the input impedance of the chip at the operating frequency of 13.56 MHz. On the other hand, the input impedance of the chip at the EPC Gen2 port is $10.7 - j200\,\Omega$. Therefore, the input impedance of the antenna at the operating frequency must be equal to the complex conjugate of this value to achieve maximum power transfer. A T-matching technique is utilized to this purpose. Both antennas are electromagnetically simulated with the software CST Microwave Studio, and designed to achieve an input reflection coefficient better than $-15$ dB at the respective design frequencies. Fig. 4 shows the radiation patterns of the antenna at 866 MHz. The antenna is linearly polarized and its diagram is almost isotropic.

The circuit is finally manufactured and tested. A prototype is realized on an 800 $\mu$m-thick FR4 substrate (dielectric permittivity 4.9 and loss tangent 0.015). The copper traces are 35 $\mu$m thick. The chip is soldered to the antennas with a soldering paste. The photo of the obtained prototype is shown in Fig. 5.

Alternatively, the transponder can be easily manufactured on a flexible substrate and then stuck on the bottom of a button. Firstly, the NFC transponder has been tested. The transponder has been interrogated with a commercial NFC reader integrated in a phone, as shown in Fig. 6. The phone

**FIGURE 7.** Test of the UHF transponder. The tag is interrogated with the Thing-Magic Nano - RAIN RFID reader in a realistic environment.

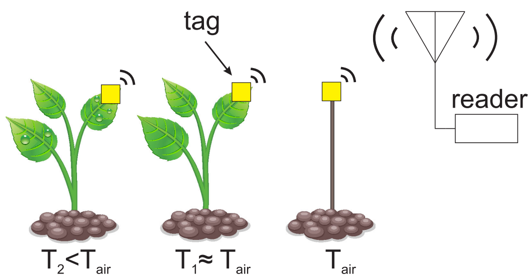
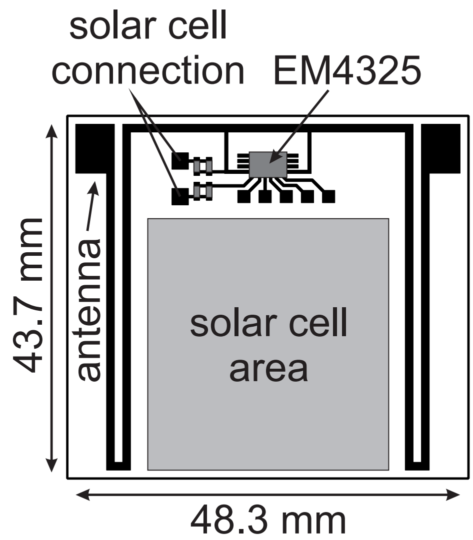
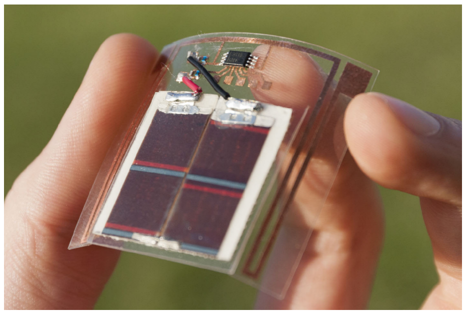



**FIGURE 8.** Scheme of the proposed RFID-based temperature sensing system for smart agriculture applications. From [54].




(a)



(b)

**FIGURE 9.** An autonomous RFID-based leaf-temperature sensor: (a) the layout and (b) a photo of the prototype. From [54].

is able to read the brief message written in the NFC memory from a distance of about 1.5 cm.

Then, the UHF transponder has been interrogated, as illustrated in Fig. 7. The Thing-Magic Nano - RAIN RFID reader has been used for interrogation. Such device is compact and low cost, although characterized by a limited sensitivity (minimum received power -60 dBm). The reader, connected to an external antenna with a broadside gain of 5 dBi at 866 MHz, is programmed with Arduino, which, in turn, is managed by a personal computer. In the experiment in Fig. 7, the reader transmits 20 dBm of power (corresponding to 25 dBm Effective Isotropic Radiated Power or EIRP) and the tag, placed at a distance of about 60 cm, is able to communicate its identification number.

### B. RFID-BASED AUTONOMOUS LEAF-COMPATIBLE TEMPERATURE SENSING SYSTEM FOR PRECISION AGRICULTURE

As a second example of applications of RFID sensor systems, let's consider a system for measuring the temperature of a leaf useful for evaluating the state of well-being of a plant that is part of a crop, in order to efficiently manage irrigation of the crop. The operating principle is described in Fig. 8; some nodes of the temperature sensor are placed on the rear face of the leaves, while other nodes are placed in the air, making sure that both nodes are not exposed directly to the sun's rays. When the plant is in a state of well-being, and therefore perfectly hydrated, the temperature of the leaf is lower than that in air [53] thanks to the phenomenon of transpiration. Therefore, by measuring the temperature difference between leaves and air, it is possible to accurately regulate the irrigation of the crop, ensuring, at the same time, the well-being of the plants and energy savings.

As explained in detail in [54], the system consists of nodes based on EM Microelectronic's EM4325 chip [52]. The chip is a Class 3 Generation 2 (Gen2) IC, which complies with ISO / IEC 18000-63, ISO / IEC 18000-64 (TOTAL), and EPCTM Class 1 Generation 2. The tag supports two operating modes: passive and battery-assisted, and supports an integrated temperature sensor having an operating range from $-40\,^{\circ}$C to $+60\,^{\circ}$C with a resolution of $0.25\,^{\circ}$C. As shown in Fig. 9(a), the chip is connected to a folded dipole antenna and uses the energy supplied by a solar cell made of flexible material, to interrogate the sensor in order to guarantee the autonomy of the transponder. The adopted square solar cell is based on four cells connected in series (model FlexRB-15-4015 from Ribes Tech) [54]. The cell is able to provide the required voltage and current for irradiance values higher than 800 lux, condition which is easily satisfied in outdoor diurnal applications. The entire system is made on a polylactic acid film, which is flexible and biodegradable (Fig. 9(b)). The metal lines necessary

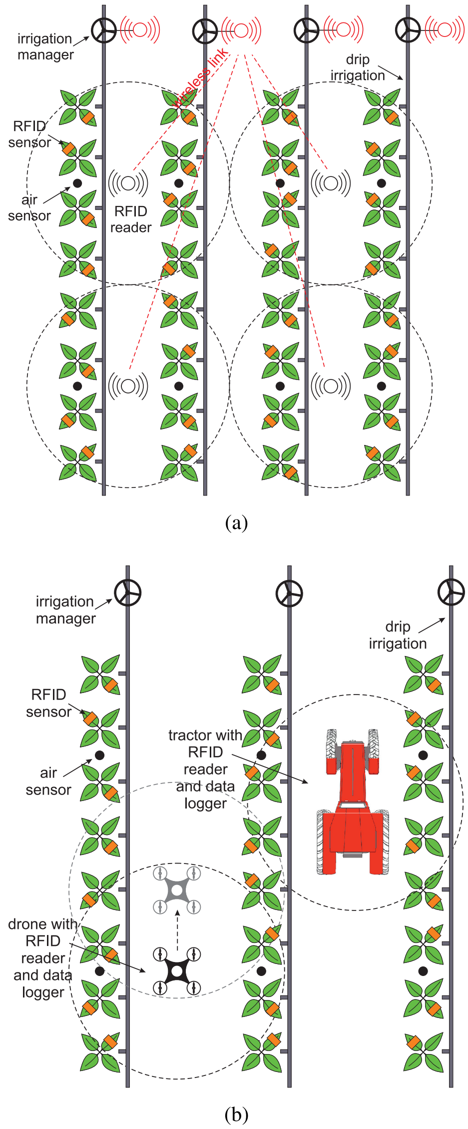



**FIGURE 10. Leaf monitoring based on Wireless RFID sensors: (a) fixed readers and (b) mobile readers. From [56].**

to make the antenna and the interconnections are printed using the photolithographic process on copper adhesive tape [55]. The circuit layout has been optimized to obtain a compact and light circuit (dimensions of about 44 mm × 48 mm and weight of about 3 g) suitable for application on a single leaf.

From the field tests shown in [54], it can be seen that the sensors are able to discriminate the variation of the water level in the plants and to be interrogated up to a distance of 2.8 m with a transmitted power EIRP of 23 dBm. In a future engineered implementation of the system, it can be thought of integrating the solar cell on the same substrate as the sensor and depositing the metallizations with the ink-jet printing technique, thus creating an even more compact and low-cost circuit. Possible application scenarios, in the field of precision agriculture, are illustrated in Fig. 10; Fig. 10(a) shows a crop irrigated with the drip system. Wireless sensors are applied to the leaves of a number of plants. The RFID readers are distributed throughout the field to cover the entire cultivated area. The readers are connected to the irrigation system via a wireless link (for example a WiFi network). The sensors in the air may be fewer in number than the sensors on the leaves (assuming a temperature that varies slightly in the area affected by the measurements). This system allows us to have an instant picture of the well-being of the plants and consequently allows us to adequately irrigate the plantation.

The system can be further optimized by mounting the RFID readers on vehicles (tractors, drones) that move regularly along the rows of cultivation, collecting data on a data logger and downloading them at the end of the path (Fig. 10(b)). This approach allows us to reduce the number of necessary readers and consequently reduces the cost and complexity of the system but does not allow to have instant data.

### *C. HARMONIC TAGS FOR ELECTRONIC ARTICLE SURVEILLANCE*

Harmonic transponders are a natural fit for electronic article surveillance applications. Indeed, a harmonic transponder is able to communicate its presence automatically (as the generated $2f_0$ is ascribable to the only transponder) without requiring additional electronics. This type of harmonic transponders, consisting of only antennas and frequency doubler, are also called “1-bit” harmonic tags. They can be considered sensors in a broad sense, as they operate as anti-theft solutions.

An example is shown in Fig. 11 [45]. The transponder is dual-layer, it is targeted for a fundamental frequency $f_0 =$ 1.2 GHz, and it is manufactured on a paper substrate by a technology we called “copper adhesive laminate” (parameters of the equivalent composite substrate, including both paper and the glue layers interposed between each copper layer and paper: dielectric constant: $\epsilon_r = 2.55$, loss tangent: tan $\delta = 0.05$, substrate thickness: $h = 0.3$ mm, trace conductivity: $\sigma_{cu} = 5.810^7$ S/m), described in detail in [44]. The tag is designed with the aim of reducing its environmental impact and cost, while achieving a compact layout.

The antenna system of the transponder consists of two nested annular slots tuned to operate at $f_0$ and $2f_0$, respectively, placed on the bottom layer of the transponder, as shown in Fig. 11(b). The slots are the result of the intersection of an ellipse and a concentric circle and are placed orthogonally to improve their isolation. The feedlines in microstrip technology are placed on the top layer and are proximity-coupled to the slots. They terminate on circular disc stubs, with a radius tuned to match both antennas to a 50 Ω impedance. The two antennas are linearly polarized, and have a maximum gain of about 3 dBi in their broadside direction.

The frequency doubler consists of a single series-connected commercial Schottky diode, model HSMS-2850 from Avago Technologies, a T-matching network used to achieve input matching, a short-circuited quarter-wave stub working as harmonic filter, and an LC output matching network, which operates also as a high-pass filter. Both the input and the output ports of the doubler are matched at 50 Ω. All components,

(a)

(b)

**FIGURE 11. Prototype of a 1-bit harmonic tag for electronic article surveillance applications: (a) top layer and (b) bottom layer. Area: 7.5 × 6.5 cm$^2$. From [45].**

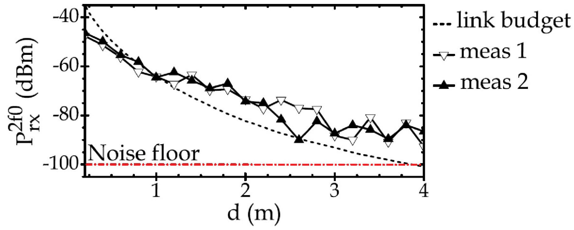



**FIGURE 12. Received second harmonic versus distance for the 1-bit harmonic tag. In "meas 1," the tag is oriented with its $f_0$ antenna in horizontal polarization, whereas in "meas 2," the tag is rotated 90° ($f_0$ antenna in vertical polarization). From [45].**

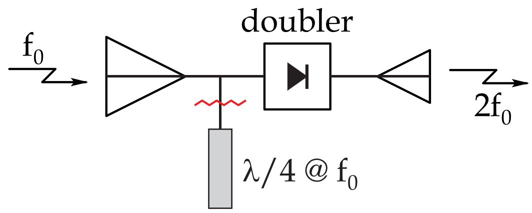



**FIGURE 13. Schematic of the proposed harmonic crack sensor. From [57].**

except for the diode, are realized in microstrip technology. The capacitor is implemented using an interdigital layout with a floating ground-plane. The lines of the circuit are folded to reduce its area occupation. This way, the doubler is placed between the two annular slot antennas. At the design frequency the doubler has a minimum conversion loss of 15.7 dB for an input power of −13 dBm.

The transponder has been tested in an indoor environment. The tag is interrogated with a transmitted power equal to 11 dBm; two circularly-polarized antennas, tuned to $f_0$ and $2f_0$, with maximum gain equal to 5 and 10.5 dBi, respectively, are used to detect the tag independently of the tag-to-reader alignment. With a receiver sensitivity of −100 dBm, a read-out distance of 4 m has been proved, independent of the tag orientation, as shown in Fig. 12, in good agreement with the link budget analysis based on (2).

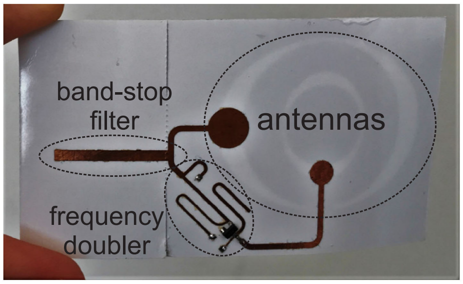
### D. CRACK SENSORS

Crack sensors are devices used to detect real-time the occurrence of cracks on surfaces of interest. They can be used in many different scenarios, ranging from building integrity monitoring, to transportation infrastructures, and to anti-tampering systems. As they are expected to be installed either in inaccessible ares or on a high number of retail goods, the possibility to use passive low-cost transponders is highly desirable.

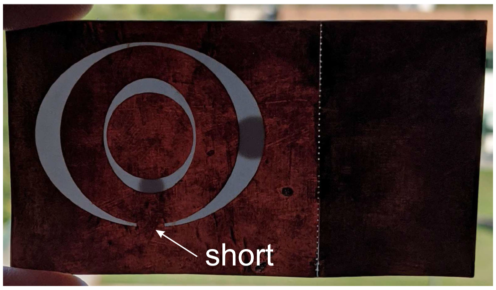
The schematic of a disposable wireless crack sensor based on the harmonic backscattering is shown in Fig. 13. A quarter-wave open circuited stub is placed between the input antenna of the transponder and the frequency doubler. For the fundamental tone $f_0$, entering from the input antenna, the stub works as a short circuit. Therefore, in quiescent condition the signal is strongly reflected and the generation of the second harmonic is hindered. If a crack occurs, instead, the stub is torn off (die cutting can be used to guarantee the complete stub removal). Therefore, nothing prevents the signal from entering the frequency doubler, and the second harmonic $2f_0$ is generated and transmitted back towards the receiver. As a consequence, the second harmonic plays the role of an alarm signal which is activated only in presence of a crack event. Despite its simplicity, the proposed system can operate in presence of multiple tags [57].

In principle the stub can be placed either at the input or at the output of the frequency doubler. In this case it is put at the input to leverage the power-dependent conversion loss of the doubler (which increases with a slope of about 10 dB/decade in its linear region if the input power decreases) to increase the dynamic range of the sensor [58].

A photo of a manufactured prototype on paper is shown in Fig. 14. The tag is designed for $f_0 = 2.45$ GHz, using the same technologies and materials described in Sec. III-C. The antennas and the frequency doubler are based on the same working principles described in Sec. III-C. Here, however, the interdigital capacitor is replaced by a lumped one and the output matching network includes also an open-circuited quarter wave stub. Concerning the antennas, a short is introduced in the annular slot working at $f_0$, to allow the microstrip feed




(a)




(b)

**FIGURE 14. Photo of the crack sensor: (a) top layer and (b) bottom layer. Area: 8.3 × 4.5 cm$^2$. Modified from [57].**

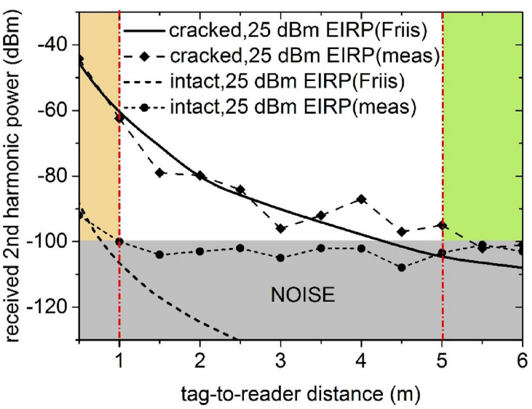



**FIGURE 15. Crack sensor experimental results. The orage area is the blind region of the system, while the green area is the non-detectable region. From [58].**

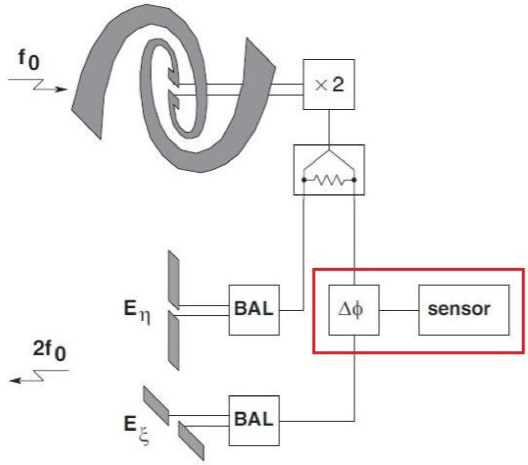



**FIGURE 16. Schematic of the proposed harmonic transponder, which encodes the sensed information in a phase difference between the two backscattered signals in orthogonal polarization. From [60].**

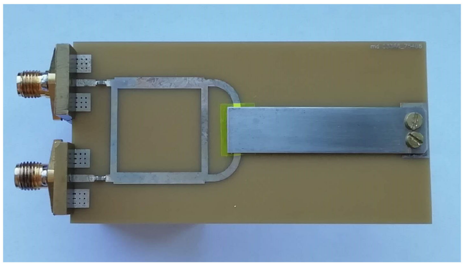
line to cross the slot. The presence of the short has a limited impact on the antenna radiation properties since it is realized in correspondence with one of the two nulls of the electric field [58].

The transponder has been tested in the two different operating states (intact and cracked). The tag is interrogated with a transmitted power equal to 12.5 dBm; two Yagi-Uda antennas, tuned to $f_0$ and $2f_0$, with maximum gain equal to 12.5 and 14 dBi, respectively, are aligned with the tag antennas, and the tag-to-reader distance has been varied from 50 cm to 6 m. The obtained results, in good agreement with the theoretical estimation based on (2), are shown in Fig. 15.

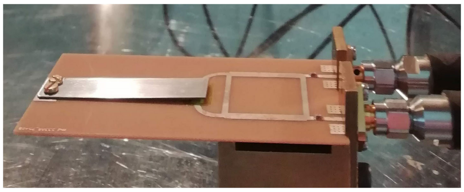
With a receiver sensitivity of $-100$ dBm, the alarm signal of the cracked tag can be detected up to 5 m. In addition to the maximum read range, we can identify also a minimum read range, i.e., a distance below which the power leakage of an intact tag (caused by the finite attenuation of the stub) is higher than the noise floor of the receiver. In the reported example the minimum distance is 1 m. To reduce this blind region a stop-band filter with a higher attenuation can be used (see for instance [59]).

### *E. TEMPERATURE SENSORS*

Harmonic-based sensor transponders can be also optimized to transmit a complex information. In Fig. 16 the schematic for an innovative harmonic transponder is proposed, where the sensor information is encoded in the phase difference between two harmonic signals transmitted by two orthogonal antennas, one acting as the reference for the other. In particular, the tag receives the interrogating signal at the fundamental tone $f_0$ which is fed into a passive (i.e. Schottky or varactor diode) frequency multiplier. The generated second harmonic, $2f_0$ is split in two parts by a power divider. One of these two signals is radiated back to the reader using a linearly polarized antenna (e.g. a dipole, a microstrip patch, etc.). This is a sort of reference signal for the system. The phase of the other signal, instead, is altered according to the sensor data and then is radiated back using a second antenna with an orthogonal polarization with respect to the first one. In this way, it is possible for the reader to recover the phase shift between the two second harmonic signals (a simple I/Q receiver can be used), irrespective of the distance between reader and tag. A key element of this system is the phase shifter that encodes the sensor data. It should be completely passive to avoid batteries, and it should be able to encode the information associated with the measured physical parameters in the phase shift of a microwave signal. To this purpose, a temperature transducer has been developed, based on a reflection-type phase shifter and a bimorph cantilever [61]. A photo of the prototype is shown in Fig. 17.



(a)



(b)

**FIGURE 17.** **Photo of the proposed passive temperature transducer. (a) top view and (b) perspective view at 50 °C. From [61].**

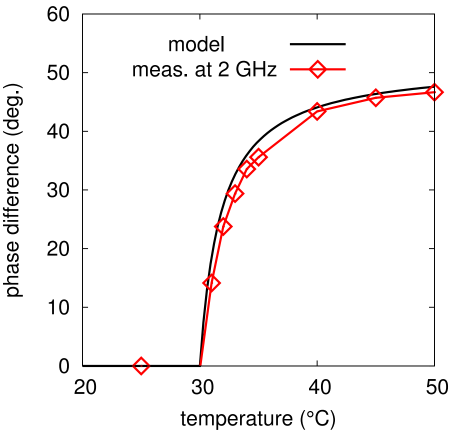



**FIGURE 18.** **Temperaure transducer experimental results. Comparison between the modeled and the measured phase difference at 2 GHz versus temperature. All phase values are referred to the phase of the transmission coefficient of the circuit for $T = 30$ °C. From [61].**

It consists of a branch line coupler, designed to operate at 2 GHz, where the direct and coupled ports are closed on two identical variable capacitances implemented by a bimorph cantilever. The cantilever is a strip composed by two metal layers stuck together with different thermal expansion coefficients. One end of the cantilever is anchored to the PCB, while the other is free to move and overlaps the terminal pads of the direct and coupled ports of the branch line, thereby forming parallel plate capacitors (a mylar layer, the yellow square in the photo, is used to avoid the short circuit between the pads and the cantilever). As the temperature changes the cantilever bends, thereby changing the distance between the two plates (i.e., the pads and the cantilever), which causes a change in the capacitance value and, consequently, a change in the phase of the transmission coefficient of the circuit.

A prototype has been finally manufactured and tested in a climatic chamber. The obtained results are shown in Fig. 18. We can identify a threshold temperature at about 30 °C where the cantilever is flat. Below such temperature the bending is not allowed by the PCB, so the phase is constant. Above such temperature, instead, the phase changes, and a maximum phase variation of 47 ° is experienced in the temperature range from 25 to 50 °C.

## IV. CONCLUSION

A review of wireless transponders based on RFID and harmonic backscattering for sensing has been reported. A description of the working principle of such transponders has been provided as well, highliting their potential and main features. Aspects such as read range, cost, environmental impact, power consumption, and form factor, have been taken into account and discussed throughout the paper. The variety of the adopted solutions and application scenarios for the proposed transponders testifies the versatility of RFID technology, and brings to light the key role of this technology in the evolution of the IoT.

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