Self-sensing Passive RFID: from Theory to Tag Design and Experimentation

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***Abstract*— A passive UHF RFID system may be used as a self-sensing devices able to sense the geometrical and physical variation of the tagged object without the use of any specific sensor. This possibility is constrained to the design of multi-chip tags and to the definition of proper measurements modalities. This theoretical idea is here fully demonstrated experimentally for what concerns the wireless monitoring of the change of materials inside a plastic container. The paper describes some measurement techniques and simple data inversion algorithms.**

I. Introduction

The passive UHF tag is often considered, in the RadioFrequency Identification (RFID) context [1], as a digital device which, when interrogated and energized by a reader, may send back its own ID, or other resident information by a backscattering modulation of the incident continuous wave. Beside this common usage of the RFID, an analog processing of the physical signals related to the read-tag communication, could permit to achieve much more information about the target without the need of additional electronics or sensors. The rationale of this idea lies in the clear dependence of the tag's input impedance and radar cross section on the physical and geometrical features of a real target. It is well experienced that, when a same tag is placed onto different targets, the tag antenna's input impedance may in some cases undergo a mismatch and consequently a change of the read distance and of the backscattered power can be observed. A first theoretical investigation of the tag's sensing capabilities was presented in [2] with some partial experimental evidence of the basic idea. Further self-sensing procedures, involving both a single and multiple chips are described in this contribution, with great attention to prototyping and full experimentations.

II. Self-Sensing equations

The two-way reader-tag link may be characterized by the equations of the power collected at the microchip (1) and the power backscattered [3] by the tag to the reader (2) and collected by this one:

$$P_{R\to T} = \left(\frac{\lambda_0}{4\pi d}\right)^2 G_R(\theta,\phi)G_T(\theta,\phi,\Psi)\tau(\Psi)\eta_p P_{in} \qquad (1)$$

$$P_{R\leftarrow T} = \left(\frac{\lambda_0}{4\pi d}\right)^4 G_R^2(\theta,\phi)G_T^2(\theta,\phi,\Psi)\rho(\Psi)\eta_p^2 P_{in} \qquad (2)$$

where 'Ψ' generically indicates a physical or geometrical parameter of the target which has to be monitored by the RFID platform (for instance the dielectric permittivity, the thickness or the temperature). d is the reader-tag distance, G_R is the gain of the reader antenna, G_T is the gain of the tag's antenna when placed on the target. P_{in} is the power entering in the reader antenna, and τ is the power transmission coefficient of the tag, defined as

$$\tau = \frac{4R_{chip}R_A(\Psi)}{|Z_{chip}+Z_A(\Psi)|^2} \qquad (3)$$

η_p is the polarization mismatch between the reader and the tag and

$$\rho(\Psi) = \frac{4R_A^2(\Psi)}{|Z_{mod}+Z_A(\Psi)|^2} \qquad (4)$$

is a function of the antenna impedance related to the tag's radar cross-section and to the modulation impedance $Z_{\rm mod}$ of the microchip to encode the low and high digital state.

The tag is activated when the absorbed power exceeds the tag's microchip sensitivity threshold p_T, e.g. when $P_{R\to T} > p_T$.

Both P_{in} and $P_{R\leftarrow T}$ are measurable quantities by the reader and they indirectly embed some physical information about the tag's features. Nevertheless additional data are required to remove the generally unknown dependence on the reader-tag's orientation and distance within a non-cooperative context. This goal may be achieved at least by the two procedures described next.

A. Single-chip sensing

A first solution to extract some target's physical information from the reader's measurements is to take the ratio $P_{R\to T}^2/P_{R\leftarrow T}$ at the minimum reader's power P_{in} required to activate the tag (*turn-on power*). In this case the power collected by the microchip, $P_{R\to T}$, will be, by definition, the microchip sensitivity p_T and the above ratio becomes

$$\frac{p_T^2}{P_{R\leftarrow T}} = P_{in}\frac{\tau^2(\Psi)}{\rho(\Psi)} \qquad (5)$$

where the dependence on orientation and distance disappears. In case the tag's modulating impedance was the microchip impedance itself ($Z_{\rm mod} = Z_{chip}$) then the previous equation may be rewritten as

$$\bar{P}(\Psi) \equiv \sqrt{P_{in} P_{R \leftarrow T}} = \frac{p_T}{2R_{chip}} |Z_{chip} + Z_A(\Psi)| \quad (6)$$

The term $\bar{P}(\Psi)$ is the geometrical average between the input threshold power and the backscattered power and is a measurable quantity, indirectly related to variation of the target's parameter through the change of the tag impedance. It is therefore possible to numerically or experimentally develop a *calibration curve* $\bar{P} \leftrightarrow \Psi$ relating the variation of the measured response of the tag to the variation of the target, with no a-priori information about the tag-reader mutual position.

B. Multi-chip sensing

A different type of calibration curve may be obtained by the recently introduced [2] concept of *multi-port tags.* The method includes a UHF tag antenna provided with multiple microchip transponders (at least two). The multi port tag can be achieved as either a *cluster* of N cooperating single-chip tags co-located onto a same target, or a single tag provided with N input ports. When a cluster of passive RFID tags (antenna plus Integrated Circuit -IC- transponder), or a single multi-port tag having distinct transponders, are deployed on a same target, several correlated backscattered signals are originated. Each of them is labeled by the unique identification code (ID) of the responding IC.

The unknown reader-tag distance is now dropped by calculating the *backscattered power ratio* p_{ij} between the received powers in (2) from two different ports:

$$p_{ij}(\theta, \phi, \Psi) \equiv \frac{P_{R \leftarrow T,i}}{P_{R \leftarrow T,j}} = \left[\frac{G_{T,i}(\theta, \phi, \Psi)}{G_{T,j}(\theta, \phi, \Psi)} \right]^2 \frac{\rho_i(\Psi)}{\rho_j(\Psi)} \quad (7)$$

However, p_{ij} is still affected by the uncertainty on the tag orientation (θ, ϕ) with respect to the reader. It is therefore required that the multi-port tag design satisfies the additional condition of gain patterns proportionality, e.g. that

$$\frac{G_{T,i}(\theta, \phi, \Psi)}{G_{T,j}(\theta, \phi, \Psi)} = K(\Psi) \quad (8)$$

and hence the resulting calibration curve is

$$p_{ij} = \frac{P_{R \leftarrow T,i}}{P_{R \leftarrow T,j}} \leftrightarrow \Psi = K^2(\Psi) \rho_i(\Psi) / \rho_j(\Psi) \quad (9)$$

where ρ_i is related through (4) to the input impedance at $i$the port of the antenna.

Alternatively p_{ij} may by defined as the ratio between the turn-on powers ($P_{in,i}$) of the two microchips (from (1)), and under the same pattern condition as in (8), a third calibration curve may be obtained:

$$\tilde{p}_{ij} \equiv \frac{P_{R \to T,i}}{P_{R \to T,j}} = \frac{P_{in,i}}{P_{in,j}} \leftrightarrow \varepsilon = K^{-1}(\Psi) \tau_j(\Psi) / \tau_i(\Psi) \quad (10)$$

It is worth noticing, that unlike the single-chip measurement, the multi-chip sensing procedure is sensitive to the variation of both impedance and gain.

The multi-chip approach, although it is more complicated than the turn-on power measurement since involves two microchips and more challenging antenna design to achieve the gain condition in (8), nevertheless it may offer the additional possibility to shape the calibration curves for a requested resolution and dynamics (see [2] for full details).

III. Experimental analysis

Simple planar dipole antennas, with T-match impedance adapter, have been designed and fabricated with the purpose to evaluate the proposed sensing procedures in realistic configurations. The tags are rather conventional since the main interest here is to experimentally check the validity of self-sensing concepts.

The experiments consider the wireless monitoring of the filling level of plastic containers with both low- (sugar powder) and high-dielectric contrast (water). The two cases are very challenging since the geometrical variation of the first material is expected to only slightly modify the attached antenna's features, as opposite to the second material whose effect on the antenna impedance and related functions could be not monotonic and hence the extraction of a useful calibration curve could be in every case rather tricky.

In all the cases the antennas are designed to match a microchip with input impedance $Z_{chip} = 15 - j135\Omega$ and the required numerical simulations have been carried out by a FEM code. It is worth mentioning that the various antennas have been designed not in the free space, but when attached onto the real target having particular values of the parameter Ψ as specified next.

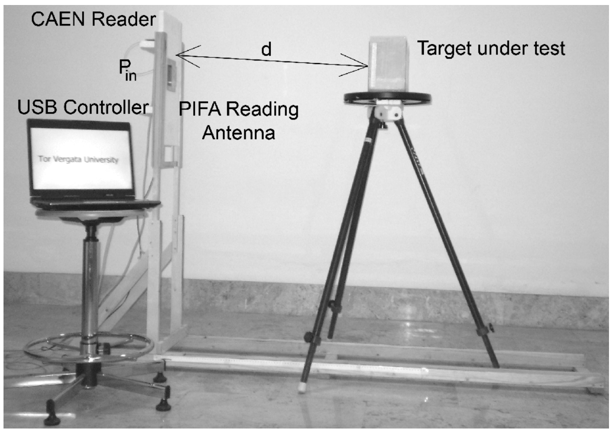

Fig. 1. Measurement set-up comprising a low-range reader, a PIFA linear-polarized antenna and a computer controller.

The measurement set-up (Fig. 1) comprises the short-range reader CAEN A528 incorporating the INTEL RFID chipset UHF- R1000 [4] able to provide the RSSI backscattered power. The interrogating antenna was a quarter-lambda patch (PIFA) with maximum gain of 3.0dB. The measurements were made within a large bare room wherein the reader's antenna and the tag-under-test were placed at 1.2m from the ground. The reader was controlled by a personal computer able to set the interrogation rate, the emitted power and to collect the backscattered signal strength from single and multiple tags. Since power emitted by the reader is only controllable with discrete variations, e.g. $P_{in}^{(n)} = \{10, 14, 17, 20, 23, 25, 26.5\}dBm$, a measurement trick was used to refine the control on the power density impinging the tag. Having fixed an initial reader-tag distance $d = 50cm$ the power emitted from the reader is increased up to the smallest value $P_{in}^{(k+1)}$ making the tag responding. Then the power value is reduced to the closest discrete value $P_{in}^{(k)} < P_{in}^{(k+1)}$ (the tag is unreachable in this case) and the reader-tag distance is hence continuously reduced down to a value d_0 for which the tag will again respond (thanks to the increased power density impinging the tag). The turn-on power is now found with improved resolution and the value $P_{in}^{(k)}$, as well as the received backscattered power $P_{R \leftarrow T}(d_0)$ at the actual reader-tag distance d_0 are used to calculate the function in (6). In all the measurements the tag is considered to be responding when the rate of successfully interrogations (integrity CRC code positive) is 100**%**.

A. Sensing low-dielectrics

The box used for the sugar-powder ($\varepsilon_s = 2.76$, $\sigma_s = 2.44 \cdot 10^{-2} S/m$) experiment is made of perspex ($\varepsilon_p = 2.7, \sigma_p \sim 0$). The two sensing dipoles are attached onto a same face of the box (Fig.2). In this example, the parameter to be sensed is the variation of the sugar level ($\Psi \equiv h_S$). The two tags are respectively denoted as *air-tag* (TAG$_A$), for the case optimized to have the best conjugate matching to the microchip ($\tau \to 1$) when the box is empty (sugar level h_S=0cm), and *sugar-tag* (TAG$_S$) when the best matching is achieved for the box filled up to a level h_S=14cm. The second antenna has been deduced from the first one through a 1.2 scaling factor plus some small size refinement.

The multi port measurement is executed by gradually filling the box with sugar starting from $h_S = 0$ up to $h_S = 14cm$. The reader and the tags are aligned to have maximum polarization efficiency. The backscattered powers $P_{R \leftarrow T, air}$ and $P_{R \leftarrow T, sugar}$ are collected by the reader at a distance $d = 0.5m$ for three different values of input power at the reader port e.g. : $P_{in} = \{14, 17, 20\}dBm$. Fig. 3 shows the measured and simulated backscattered power ratio $p_{air,sugar} = P_{R \leftarrow T, air} / P_{R \leftarrow T, sugar}$ when the experimental data are averaged on 50 successfully readings.

Measurements and simulations are in good agreement and it is observed a nearly linear 10dB dynamics, at least up to $h_S = 12cm$. The measured outcomes are weakly dependent on the transmitted power and the calibration curve seems to permit a continuous monitoring of the filling percentage of the box so that a change of 1cm in the sugar level will produce a variation of 10% in the received data.

The single-chip sensing experiment, according to the procedure described in paragraph II.A, has been executed using the only TAG$_A$, and repeating the estimation of the threshold input power in (6) for three different mutual orientations $\phi_0 = \{0°, 45°, 180°\}$ between reader and tag on the horizontal plane

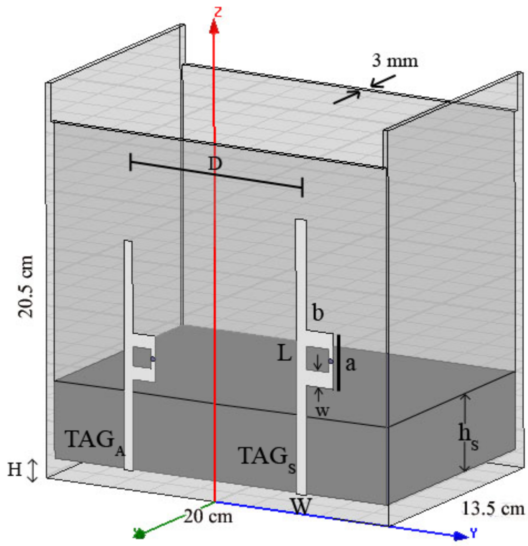

Fig. 2. Passive tags to sense the level of sugar powder within a perspex box. Geometrical size (in [mm]): H=12, D=95; TAG$_S$ L=142.8, W=6, a=28.8, b=15.6, w=8.4; TAG$_A$ L=119, W=5, a=24, b=13, w=7.

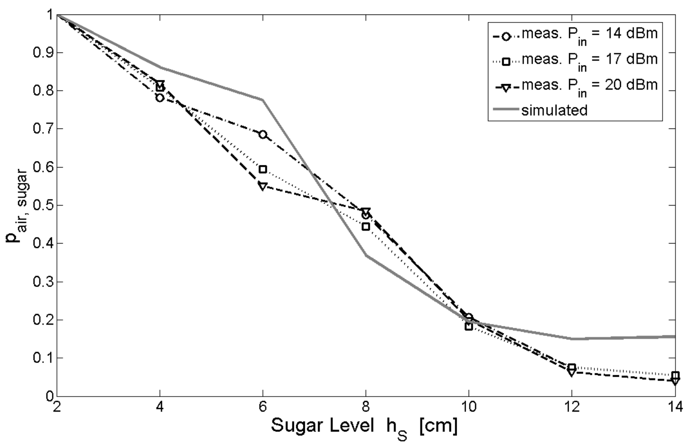

Fig. 3. Sugar box: Normalized simulated and measured backscattered power ratio $p_{ij} = \frac{P_{R \leftarrow T,i}}{P_{R \leftarrow T,j}}$ for the multi-chip system which is monitoring the sugar level inside the box. The measurements have been repeated for some input powers.

so that $\phi_0 = 180°$ corresponds to have the box interposed between reader and tag.

The diagram in Fig. 4 gives the theoretical and experimental calibration curves which look rather different from that obtained with the multi-chip procedure. In particular the measured signals' dynamic is narrower (about 3dB) and the measured data starts to exhibit some significant change only for variation of the sugar content exceeding 6-8 cm. The shape of the curves is not substantially dependent on the observation angle, as expected from how the calibration curve has been defined, even if some differences may be observed in the local values. This sensing modality appears less suited to a continuous monitoring of the variation of this kind of targets but may provide an on-off information about the filling state of the container so that a low measured data ($\sqrt{P_{in}P_{R\leftarrow T}} < 0.75$) means that the filling level is decreased below half the antenna size.

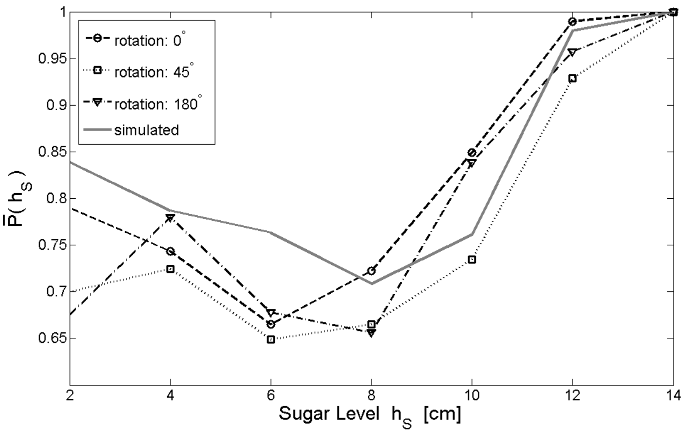

Fig. 4. Sugar box: (Normalized) Calibration curve $\bar{P}(h_s) = \sqrt{P_{in}P_{R\leftarrow T}}$ obtained by the turn-on measurement techniques involving the only TAG$_A$. The data acquisition has been repeated for different orientation, on the horizontal plane, between reader and tagged box.

B. Sensing high-dielectrics

Two water containers having different size and shape, box and a small cylinder, are considered in this second experiment. The tag antennas are again simple dipoles matched to the microchip when they are placed over filled containers. For brevity, the only results with single-chip measurements are here reported. The water level was changed from h_W=0cm to h_W=8cm (box) and 12cm (cylinder). The measured calibration curves, obtained as described above are reported in Fig.5 and Fig.6.

Unlike the previous example of sugar box, the curves are now monotonic for most the variation of the water and the dynamics of the received signal range is 1:0.7 and 1:0.5 in the case of box and cylinder, respectively. This behavior seems to be suited for a continuous monitor of the level's variation.

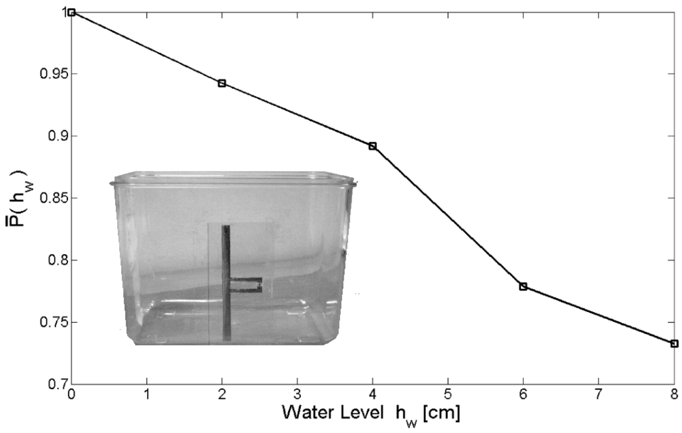

Fig. 5. Water box (140 × 90 × 110)mm: (Normalized) Calibration curve $\bar{P}(h_W)$ for the monitoring of the variation in the water content. The tag's size (in [mm]) are given with the convention of Fig.2: L=80, W=5, a=10, b=20.26, w=3.

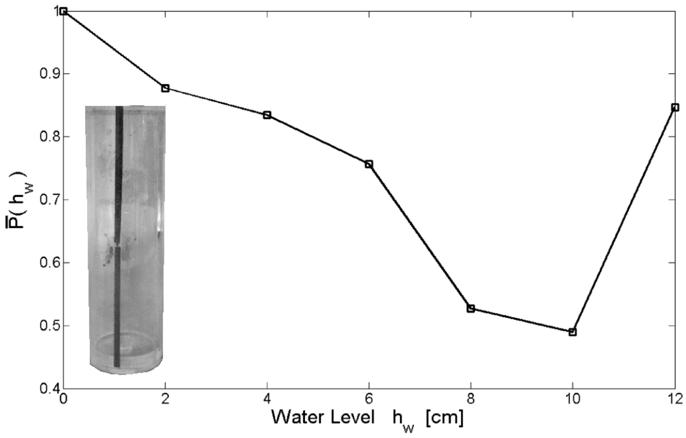

Fig. 6. Water cylinder (radius 22mm, height 148 mm): (Normalized) Calibration curve $\bar{P}(h_W)$ for the monitoring of the variation in the water content. The tag's lengh $L = 138mm$ and width $W = 2mm$.

IV. CONCLUSIONS

The use of RFID passive tags as true analog transponders opens the way to several new low-cost applications. The developed passive sensing techniques, although still in the embryonic stage, has been demonstrated to be feasible within the existing commercial technology. The single-chip sensing may in principle use conventional tags, already on the market, but they nevertheless require a rather complicated measurement procedure whose the key-point is the possibility to control the emitted power with fine steps. From these preliminary experiments, the single-chip procedure seems to work better with high-density materials.

The multi-chip sensing, instead, requires much more elecromagnetics and antenna design effort, but it promises, by means of a simpler measurement, a larger dynamics and hence a better resolution. More stable readings could be achieved by increasing the number of acquisitions, for instance moving the reader all around the object, so to apply more advanced data inversion techniques common in the Remote Sensing context.

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REFERENCES

[1] D. M. Dobkin, The RF in RFID: passive UHF RFID in Practice, Elsevier, Amsterdam, 2007

[2] G. Marrocco, L. Mattioni, C. Calabrese, "Multi-port Sensor RFIDs for Wireless Passive Sensing - Basic Theory and Early Simulations", *IEEE Trans. Antennas Propagation.*. vol.56, n.8, pp.2691-2702, Aug. 2008

[3] P.V. Nikitin, K.V.S. Rao, "Theory and Measurement of Backscattering from RFID Tags", *IEEE Antennas and Propagation Magazine*, Vol. 48, No. 6, pp. 212-218, Dec 2006.

[4] S. Chiu, I. Kipnis, M. Loyer, J. Rapp, D. Westberg, J. Johansson, P. Johansson, "A 900 MHz UHF RFID Reader Transceiver IC", *IEEE Journal of Solid-State Circuits*, Vol.42, N.12, pp.2822-2833, Dec. 2007