# Passive RFID based sensing

S. Capdevila, L. Jofre, J. Romeu
AntennaLab, Department of Signal Theory and Communications
Universitat Politècnica de Catalunya
08034, Barcelona, Spain
email: scapdevila, jofre, romeu@tsc.upc.edu

J.C. Bolomey
Electromagnetics Department,
Supelec
91192 Gif-sur-Yevette, France
email: jean-charles.bolomey@supelec.fr

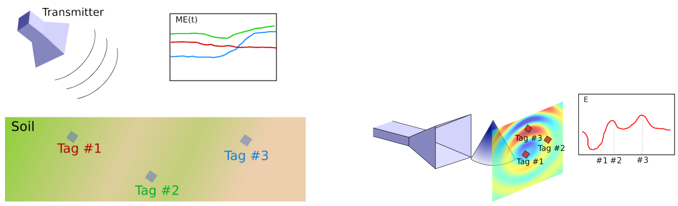
***Abstract*—The principle of communication of passive RFID, which relies on the Modulated Scattering Technique (MST) to transmit the information from the tag to the reader, opens a way to enable conventional RFID for sensing purposes, without any additional circuitry. In this paper a short description of the physical principle behind the sensing is presented along with measurements of RFID tags used for sensing in multiple applications, such as electromagnetic field measurement temperature or presence detection.**

## I. Introduction

A growing number of applications require the acquisition of information of some physical parameter around or inside of complex media; the deployment of wireless sensors networks poses a good opportunity to obtain this information for applications such as health caring [1], structural monitoring [2]–[4], inventory tracking [5] or security applications. In most of the cases such solutions rely on active devices, for which the sensors are powered by a battery or directly plugged into a wired power supply although there exist passive solutions that extract the energy to operate from the neighborhood of the sensors through the use power-harvesting techniques. Both approaches have their advantages and drawbacks, for instance the former presents the best range coverage and sensitivity, and the latter presents a longer lifetime since they do not rely on a battery. In this context passive RFID, in spite of having been initially deployed for identification purposes, becomes a feasible platform as a sensing probe. The research on RFID sensing rely on the use of environmental-dependent materials [6], [7], the addition of specific sensors in the circuitry [8], [9], or the study of the evolution of the signal of the RFID tag with variation on the physical quantities of interest [10]–[15].

In this paper two different RFID sensing applications are explored, as presented in Fig. 1; in the first one RFID tags are used to sense the temperature around the tag. In the second, the tags are used to measure a field distribution created by the reader antenna, which could be used for instance for imaging applications

This work was supported in part by the Spanish Interministerial Commission on Science and Technology (CICYT) under projects TEC2007-66698-C04-01/TCM ,TEC2010-20841-C04-02 and CONSOLIDER CSD2008-00068 and by the “Ministerio de Educación y Ciencia” through the FPU fellowship program.




(a) Soil moisture (b) EM field distribution

Fig. 1. Two possible scenarios to use RFID tags for its sensing capabilities

## II. Formulation

This section presents a short introduction to formulation that is the basis for the following discussion in sections III and IV. A more detailed discussion on the electromagnetic formulation of RFID can be found in [16]–[18].

A typical scenario of the communication in RFID is presented in Fig. 2, where the horn antenna acts as the reader antenna, and the tag is placed in a complex scenario, with some objects placed between tag and reader. Passive RFID tag communicate through backscattering, that is the same principle of operation of MST [19], and consists in a variation of the reflection coefficient of the RFID, by means of a change in the input impedance of the RFID IC between two states $Z_{L_{1,2}}$. Under this mode of operation the signal received by the reader $(b)$ present several components:

$$b = b' + b_{SM} + b_{AM} \tag{1}$$

where $b'$ refers to reflections on the scenario, $b_{SM}$ is the structural reflection of the RFID tag and $b_{AM}$ is its antenna mode reflection, which will depend on the specific load attached to the antenna. To obtain an expression for $b_{AM}$, a reciprocity formulation is adequate to take into account the complexity of the scenario, since it imposes only the condition

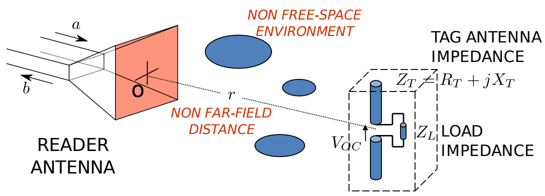



Fig. 2. A typical RFID scenario, where obstacles and other media might be between reader and the RFID tag

of linearity on it. Under this conditions it can be shown that the antenna mode component of the input reflection coefficient ($\rho_T^{AM}$) will be:

$$\rho_T^{AM} = \frac{b_{AM}}{a} = \frac{V_{OC}^2}{2P_a}\frac{1}{Z_T + Z_L} \tag{2}$$

The first term is defined as the transfer impedance $Z_{tr} = \frac{V_{OC}^2}{2P_a}$ and is dependent of the scenario and configuration of the transmitting and receiving antennas.

In order to isolate this component, the differential reflection coefficient for the two different loads ($Z_{L_{1,2}}$) is:

$$\Delta\rho_T^{AM} = Z_{tr}\frac{Z_{L_2} - Z_{L_1}}{(Z_T + Z_{L_1})(Z_T + Z_{L_2})} = -Z_{tr}\frac{\Delta\tilde{\rho}_L}{2R_T} \tag{3}$$

where $\Delta\tilde{\rho}_L = \tilde{\rho}_{L_2} - \tilde{\rho}_{L_1}$ is the differential complex reflection coefficient.

## III. Electromagnetic Field Measurements

To measure the field in a certain region, it is necessary the use of small EM-sensors, capable of retrieving the field value introducing as little disturbance in the field as possible. The use of wired RF solutions, although it gives the best signal to noise ratio, is not ideal for every scenario, as RF cabling tends to be bulky and may introduce disturbances, and it is unable to probe the field at inaccessible points, such as within a body. An indirect measurement principle, such as Modulated Scattering Technique (MST) [19], is usually used to overcome these difficulties. Nevertheless conventional MST bases its modulation in low frequency cabling, or optical fibers [20] in order to introduce the modulation on the sensor probe. This again is not suitable for embedded sensors, where line of sight might not exist. Passive RFID tags can overcome all those difficulties since they are completely autonomous in their modulation scheme, and also they do not require any conventional external power supply, neither a battery nor cabling.

The underlying principle for EM field measurements using RFID tag [15], [21] is seen rewriting equation (3) in terms of the effective length of the tag antenna ($h_{eff}$):

$$\Delta\rho_T^{AM} = \frac{h_{eff}^2 \cdot E_{inc}^2}{2P_a} \cdot \frac{\Delta\tilde{\rho}_L}{2R_T} \tag{4}$$

where $E_{inc}$ stands for the incident field upon the tag. Measuring the response of a tag at a set of different positions, only the term $E_{inc}$ changes, and therefore the variations in the measurement represent the variations of the field distribution.

### A. Non-linearities of the RFID IC impedance

Although the previous statements are correct for MST probes, it is not completely accurate for RFID tags. Due the lack of battery and the presence of a rectifying circuit to supply energy through scavenging of the incident wave, the RFID IC has a non-linear behavior, and therefore its input impedance will change with the incident power. Fig. 3 presents the variation in the input impedance of an Alien Higgs 2 RFID IC for the scavenging state. Such variation implies that the term $\Delta\tilde{\rho}_L$ in (4) changes with the magnitude of the incident field, and so the measured field distribution must be calibrated for correct measurement of the field, as shown experimentally in the following section.

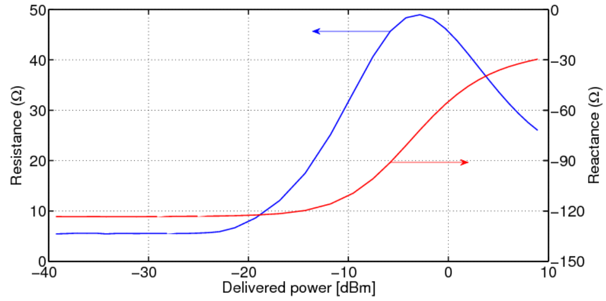



Fig. 3. Input impedance for the scavenging state of an Alien Higgs 2 RFID IC with respect to power measured using a $50\Omega$ network analyzer

### B. Ridged horn field distribution

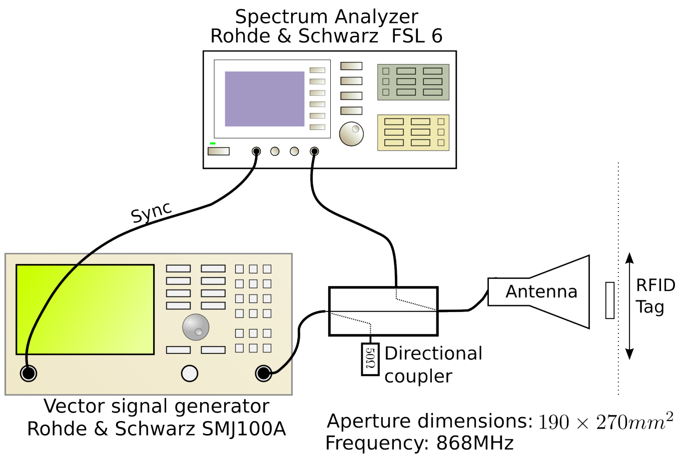
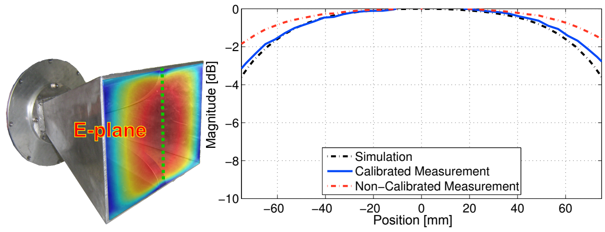


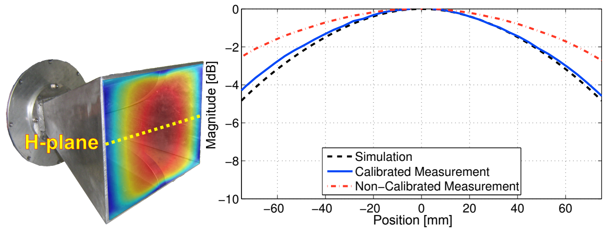

Fig. 4. Configuration used for the measurements consisting of a vector generator and spectrum analyzer to do coherent demodulation, as well as a motorized rail to scan along a line of the horn antenna aperture.

This section shows results on the measurement of a field distribution using RFID tags. The experimental setup shown in Fig. 4 is used for the measurements. It consists of a Rohde&Schwarz (R&S) SMJ100A vector signal generator and a R&S FSL6 spectrum analyzer connected to a ridged horn antenna, with an aperture of dimension $19\text{cm} \times 27\text{cm}$. The vector signal generator is used to generate the proper ASK modulation to *select* and *query* the RFID tag, and the spectrum analyzer, which is connected through a directional coupler, captures the phase and quadrature components of the response of the RFID tag, which are post-processed. The RFID tag is placed at a distance of $1\text{cm}$ of the aperture of the horn, and is on top of a linear stage to scan a line along the aperture.

Fig. 5 presents the results for the measurement of the field distribution along the E-plane and the H-plane of the aperture. It can be observed that there is a disagreement between the RAW measurement and the expected field distribution as




(a) E-plane




(b) H-plane

Fig. 5. Expected and measured field distribution for the main planes, (a) E-Plane and (b) H-plane, of the aperture of the ridged horn antenna

obtained through a MoM simulation. This disagreement is due to the non-linearities as introduced in the previous section, which as shown in [15] introduce a deviation with respect to the proper field distribution:

$$\frac{\Delta\rho_T^{AM}}{\Delta\rho_T^{AM}} = \left(\frac{E_{tr}(r)}{E_{tr}(r_{ref})}\right)^2 \cdot S\left(\frac{P}{P_{ref}}\right) \tag{5}$$

where $S$ is the deviation factor, that can be characterized measuring the change in the response of the RFID tag at a fixed position for a varying controlled power, see Fig. 6. By

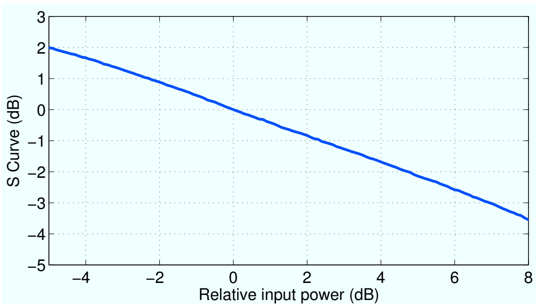



Fig. 6. This curve presents the variation of the measured response with respect to the input power, once it has been normalized by this power. For a linear device, it should be a constant of 0dB, but due to the non-linearities present in the RFID IC, it presents a variation with power

taking into account this characterization, (5) is solved and the calibrated curves shown in Fig. 5, are obtained showing good agreement with the expected field distribution.

Although until now a single moving tag has been presented as the RFID-EM probe, the same procedure can be used for an array of RFID tags. In this case the array is composed of 4 ALN-9529 Squiggle-SQ tags separated a distance of $60\mathrm{cm}$. Using the same experimental setup as before, and by doing a partial movement of the linear stage, the RAW

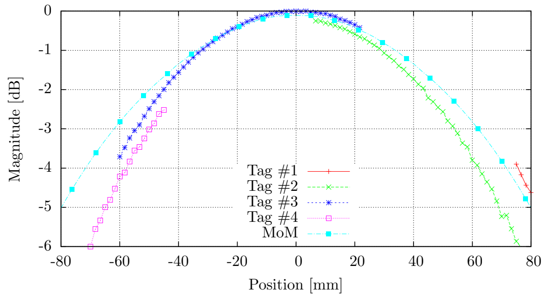



Fig. 7. Expected and measured field distribution for the each of the RFID tags along the H-plane of the horn aperture

measurement of Fig. 7 is obtained. Two things can be remarked for this measurement; on one hand, each of tags gives a slightly different response as compared with the others, this is explained due to slight differences in the tag antennas, and more importantly on the input impedances of both the antenna and the IC, which clearly introduce a variation in the reflection coefficient; on the other hand as expected after the behavior shown for the single element, there is the non-linearity effect for each of the tags. It must be noted that due to differences in the RFID ICs, the non-linearities must be characterized for each tag, since the curve might present slight variations between tags, in the same way that sensitivity levels change slightly between tags. Nevertheless, provided that the characterization of the power response of the RFID tag has been done for the same position of the tags, the calibration of the non-linearities equalizes the response of the different RFID tags as shown in Fig. 8

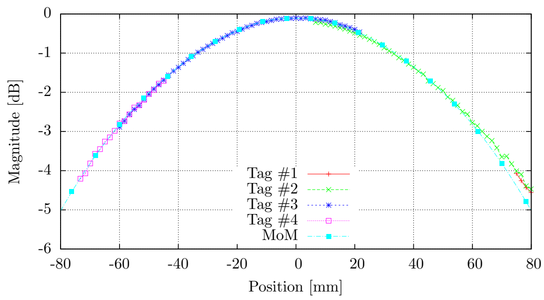



Fig. 8. Expected and calibrated field distribution along the H-plane of the horn aperture

## IV. Environment Monitoring

In this section some results are presented that use RFID sensors to monitor a physical parameters, such as temperature, the level of a liquid in a container, among others. The fundamental basis on this measurement is again seen from equation (3), where the main parameter that is changed is $Z_T$ and as such $\Delta\tilde{\rho}_L$.

### A. Continuous monitoring: temperature

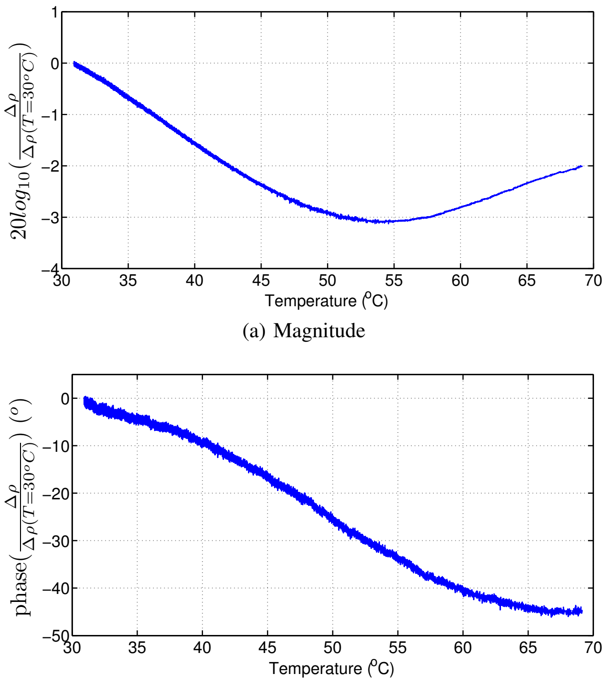
The dielectric properties of many media have a strong dependence with physical parameters, such as temperature or chemical concentration. For instance, the real part of the permittivity of water at $3GHz$ changes from $\epsilon_r = 80$ to about $\epsilon_r = 52$ for a temperature variation from $0^oC$ to $100^oC$, [22]. If such medium is near to the antenna, or the antenna is totally enclosed in the medium, a change in the temperature of water introduces variations in the propagation characteristics of the waves, and also in the input impedance of the antenna. The immersion equation, [19], [23], relates an antenna input impedance at a given frequency when the surrounding medium dielectric constant changes from $\varepsilon_r^B$ to $\varepsilon_r^A$.

$$Z_T\left(\omega_o, \varepsilon_r^A\right) = \frac{1}{m} Z_T\left(m\omega_o, \varepsilon_r^B\right) \tag{6}$$

where $m = \sqrt{\frac{\varepsilon_r^A}{\varepsilon_r^B}}$. By means of this equation, the effect of a change in the temperature of the surrounding medium in the term $\frac{\Delta\tilde{\rho}_L}{R_T}$ can be predicted; nevertheless the transfer impedance is generally also affected by changes in the surrounding medium: the effective length of the antenna might be affected, as well as the attenuation/delay of the propagating wave as it goes to and from the tag antenna. By having an RFID tag with two different load states we are able to obtain a single equation, therefore it is not possible to extract from a single measurement how much of the variation is due to each of the two terms ($Z_{tr}$ and $Z_T$). To distinguish them three or more loads are required to obtain at least two independent equations. This diversity is used for instance in [24], [25] for measurements of $Z_T$.

An experimental measurement of the capabilities of RFID for temperature monitoring has been carried out in the laboratory. The experimental setup is similar to the one used for the field measurement with the additional use of an Agilent 34401A multimeter to continuously acquire the information on the temperature of water in the tank using a PTC-100. This wired sensor is placed inside of a water tank heated up to $80^oC$. The RFID tag consists of a bowtie-like dipole antenna with two sets of parallel and series stub that allows a fine-tuning of its input impedance, [26]; the RFID tag was placed on one side of the water tank so that one side was exposed to air, and the other to the water, the stubs were adjusted using silver paint in order to obtain a proper match between the tag antenna and the RFID IC (**Alien Higgs 2 IC [27]**) when the water was at a temperature of $30^oC$ ($\varepsilon_B$). Fig. 9 presents a detail of the measurement setup showing that the reader antenna has a direct line of sight of the tag attached to the water tank. The heated water tank was left cooling and was constantly interrogated by the RFID reading system. Fig. 10 presents both the magnitude and phase evolution of the RFID measurement $\frac{\Delta\tilde{\rho}_L}{\Delta\tilde{\rho}_L(30^oC)}$. The response, relative to the lower temperature ($30^oC$), presents a noticeable variation of both the magnitude and phase. In fact it is clear that the phase information is uniquely related to the temperature. Here it must be pointed out that several effects are modifying the response of the antenna: the variation of $Z_T$ which would change $\Delta\tilde{\rho}_L$, but additionally it is changing the matching for the scavenging state ($\tilde{\rho}_L$) and therefore the input impedance of the RFID IC is likewise modified due to the non-linearities. This further modifies the response $\Delta\tilde{\rho}_L$.


Fig. 9. Detail of the experimental setup, the reader antenna has a direct line of sight view of the RFID tag attached to the water tank




(a) Magnitude

(b) Phase

Fig. 10. Received response of the RFID tag placed in a water tank as it cools down

## B. Discrete monitoring: liquid level

Despite the clear continuous response that is observed in applications such as temperature monitoring introduced in the previous section, there are scenarios where there is a high contrast in the environmental conditions around the sensor. For instance, a completely wireless sensor, that can measure the level of a liquid in a container is presented as an extreme scenario with two distinct situations, either the container is empty in which case the sensor is surrounded by vacuum/air, or the container is full of the liquid, which may have a high permittivity. As observed from the immersion equation (6), the impedance of the tag antenna presents a strong variation and the matching between the RFID IC and the antenna itself changes substantially between one state and the other one. In this kind of scenario, apart from variation in $\Delta\tilde{\rho}_L$ there will be a strong variation of the transferred power into the RFID IC, which sometimes may not be over the threshold power to activate the RFID IC, so the RFID tag sensors will present a strong ON/OFF transition, where the tag works or not depending on the presence of the liquid around the antenna. We can exploit this discrete nature of the RFID tags to the presence or absence of medium to create an array of equal tags in such a way that they will be sequentially turned ON (or OFF) depending on the level that the liquid arrives.


Fig. 11. Experimental setup for the water level measurement in a container using an array of 6 commercially available RFID tags. The water has been slightly colored in order to make it more visible in the pictures. The reader antenna is placed such that it has a direct view of the tags

For this measurement a set of 6 **ALN_9540** tags were placed in a water tank as seen in Fig. 11; since the tags were tuned for operation in air, the ON state occurs when there is no liquid around the tag, while the tag should remain silent when backed by water. The tags are interrogated sequentially and continuously while the tank is slowly emptied. The response of the RFID tags is measured with an antenna that has a direct line of sight of the tags, so that there is no variation due to the propagation conditions between reader and tag independently of the water level. Fig. 12 presents the results of the measurement: a sudden transition in the response of each RFID tag is observed when water reaches its level (see Fig. 13

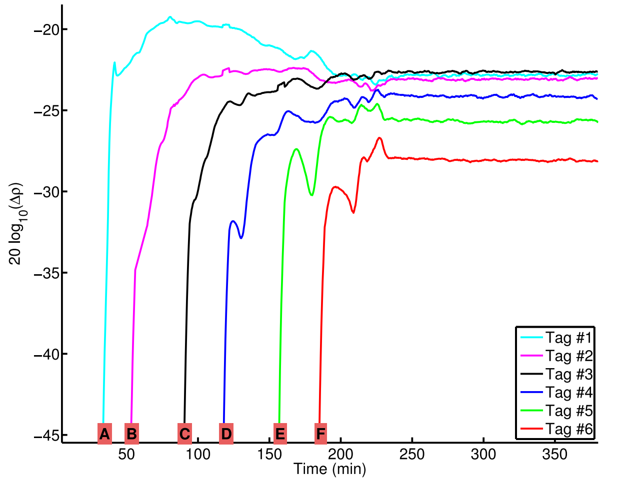



Fig. 12. Response of the 6 tags captured using the custom RFID reader as the water is being emptied. The triggering event marking the level of water can be clearly shown as the ON transition of the RFID tags.

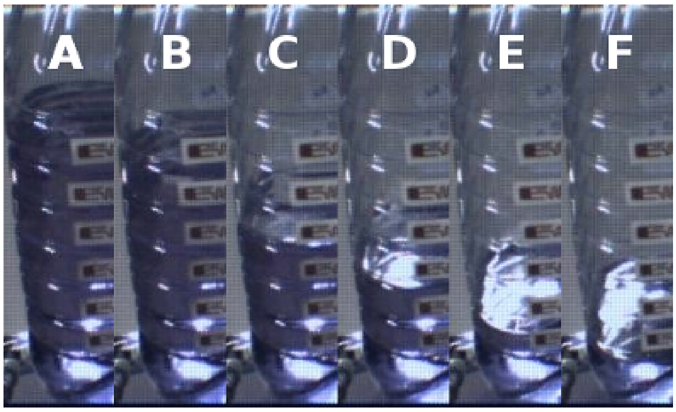



Fig. 13. Level of the water for the instant at which each of the RFID tags start answering

for a reference of the water level for each ON transition). Moreover it is interesting to note that the response of the tags does not remain constant after the transition, but rather presents a variation which is due to two different but related events, on one hand the effective permittivity seen by each tag changes with the water level, and as such the impedance values of the tag antenna are progressively modified, this is what is exploited in [28], [29], on the other hand and also affecting the impedance of the tag is the presence of the other tags, which have not been designed to reduce the coupling between them, and as water lowers the coupling between tags increase; this variations could be exploited to increase the resolution of the measurement.

## V. Conclusions

This paper has presented some experimental measurements showing some of the sensing capabilities of RFID tags, and how their response is affected by changes in its local neighborhood as well as the path between reader and tag.

Based on the modulation scheme of RFID tags, which is the same as MST, a natural sensing application of the RFID tag is its use as a EM-field probe, provided that the non-linearities effects are corrected or calibrated.

Additional sensor capabilities such as temperature measurements and liquid level monitoring have been demonstrated as feasible. Those sensing capabilities appear when the dependence of the tag antenna parameters with respect to the environment are taken into account. With commercially available RFID tags, the number of impedance states available are reduced to two states, reducing the degrees of freedom to one for solving the sensing equation. The addition of more impedance states would lead to a richer sensing data available.

## REFERENCES


[1] S. Farshchi, A. Pesterev, P. Nuyujukian, I. Mody, and J. Judy, "Bi-fi: An embedded sensor/system architecture for remote biological monitoring," *IEEE Transactions on Information Technology in Biomedicine*, vol. 11, no. 6, pp. 611–618, 2007.

[2] M. Rad and L. Shafai, "A wireless embedded sensor for structural health monitoring applications," in *Proc. 13th International Symposium on Antenna Technology and Applied Electromagnetics and the Canadian Radio Science Meeting ANTEM/URSI 2009*, 2009, pp. 1–4.

[3] J. Ong, Z. You, J. Mills-Beale, E. L. Tan, B. Pereles, and K. G. Ong, "A wireless, passive embedded sensor for real-time monitoring of water content in civil engineering materials," *IEEE Sensors Journal*, vol. 8, no. 12, pp. 2053–2058, 2008.

[4] J. Bernhard, K. Hietpas, E. George, D. Kuchima, and H. Reis, "An interdisciplinary effort to develop a wireless embedded sensor system to monitor and assess corrosion in the tendons of prestressed concrete girders," in *Proc. IEEE Topical Conference on Wireless Communication Technology*, 2003, pp. 241–243.

[5] B. Wu, Z. Liu, R. George, and K. Shujaee, "ewellness: Building a smart hospital by leveraging rfid networks," in *Proc. 27th Annual International Conference of the Engineering in Medicine and Biology Society IEEE-EMBS 2005*, 2005, pp. 3826–3829.

[6] S. Nyalamadugu, N. Soodini, M. Maddela, S. Nambi, and S. M. Wentworth, "Radio frequency identification sensors," in *ASEE Southeeast Section Conference 2004*, 2004.

[7] S. Caizzone, C. Occhiuzzi, and G. Marrocco, "RFID radio-sensor integrating shape-memory alloys," in *Proc. IEEE Antennas and Propagation Society International Symposium AP-S 2010*, July 2010.

[8] A. Ferrer-Vidal, A. Rida, S. Basat, L. Yang, and M. Tentzeris, "Integration of sensors and RFID's on ultra-low-cost paper-based substrates for wireless sensor networks applications," in *Proc. 2nd IEEE Workshop on Wireless Mesh Networks WiMesh 2006*, 2006, pp. 126–128.

[9] K. Opasjumruskit, T. Thanthipwan, O. Sathusen, P. Sirinamarattana, P. Gadmanee, E. Pootarapan, N. Wongkomet, A. Thanachayanont, and M. Thamsirianunt, "Self-powered wireless temperature sensors exploit RFID technology," *IEEE Pervasive Computing*, vol. 5, no. 1, pp. 54–61, 2006.

[10] G. Marrocco and D. Scarana, "Permittivity passive RFID sensor for non-cooperating objects," in *Proc. Second European Conference on Antennas and Propagation EuCAP 2007*, 2007, pp. 1–4.

[11] R. Bhattacharyya, C. Floerkemeier, and S. Sarma, "Towards tag antenna based sensing - an rfid displacement sensor," in *RFID, 2009 IEEE International Conference on*, 2009, pp. 95 –102.

[12] M. Tentzeris and S. Nikolaou, "RFID-enabled ultrasensitive wireless sensors utilizing inkjet-printed antennas and carbon nanotubes for gas detection applications," in *IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems, 2009. COMCAS 2009.*, nov. 2009, pp. 1 –5.

[13] G. Marrocco, "Pervasive electromagnetics: sensing paradigms by passive rfid technology," *Wireless Communications, IEEE*, vol. 17, no. 6, pp. 10 –17, 2010.

[14] R. Bhattacharyya, C. Floerkemeier, and S. Sarma, "Low-cost, ubiquitous rfid-tag-antenna-based sensing," *Proceedings of the IEEE*, vol. 98, no. 9, pp. 1593–1600, 2010.

[15] S. Capdevila, L. Jofre, J.-C. Bolomey, and J. Romeu, "RFID multiprobe impedance-based sensors," *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 12, pp. 3093–3101, 2010.

[16] F. Fuschini, C. Piersanti, F. Paolazzi, and G. Falciasecca, "Analytical approach to the backscattering from uhf rfid transponder," *IEEE Antennas and Wireless Propagation Letters*, vol. 7, pp. 33–35, 2008.

[17] P. Nikitin, K. Rao, and R. Martinez, "Differential RCS of RFID tag," *Electronics Letters*, vol. 43, no. 8, pp. 431–432, 12 2007.

[18] J.-C. Bolomey, S. Capdevila, L. Jofre, and J. Romeu, "Electromagnetic modeling of RFID modulated scattering mechanism. application to tag design," *Proceedings of the IEEE*, no. Submitted, 2010.

[19] J.-C. Bolomey and F. E. Gardiol, *Engineering Applications of the Modulated Scatterer Technique*, A. House, Ed. Artech House, 2001.

[20] H. M. Tehran, J.-J. Laurin, and R. Kashyap, "A low-perturbation near-field imager equipped with optical MST probes," in *3rd European Conference on Antennas and Propagation*, 2009.

[21] S. Capdevila, L. Jofre, J.-C. Bolomey, and J. Romeu, "RFID array probe for EM-field measurements," in *Proc. IEEE Antennas and Propagation Society International Symposium AP-S 2009*, 2009.

[22] A. Catenaccio, Y. Daruich, and C. Magallanes, "Temperature dependence of the permittivity of water," *Chemical Physics Letters*, vol. 367, no. 5-6, pp. 669 – 671, 2003. [Online]. Available: http://www.sciencedirect.com/science/article/B6TFN-479TMW9-D/2/0bd8142b16c5b751e3e5da807afd6fe3

[23] G. Sinclair, "Theory of models of electromagnetic systems," *Proceedings of the IRE*, vol. 36, no. 11, pp. 1364–1370, Nov. 1948.

[24] P. Pursula, D. Sandstrom, and K. Jaakkola, "Backscattering-Based measurement of reactive antenna input impedance," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 2, pp. 469–474, 2008.

[25] B. Monsalve, S. Blanch, J. Romeu, and L. Jofre, "A contact-less small antenna characterization through impedance modulation," in *Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on*, March 2009, pp. 696–698.

[26] S. Capdevila, M. M. Masud, R. Serrano, A. Aguasca, S. Blanch, J. Romeu, J.-C. Bolomey, and L. Jofre, "RFID based probes for EM field measurements," in *Eucap 2009*, 2009.

[27] *Higgs$^{TM}$-2 EPC Class 1 Gen 2 RFID Tag IC. Datasheet*, Alien Technology. [Online]. Available: http://www.alientechnology.com/docs/products/DS_H2.pdf

[28] G. Marrocco, L. Mattioni, and C. Calabrese, "Multiport sensor RFIDs for wireless passive sensing of objects- basic theory and early results," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 8, pp. 2691–2702, 2008.

[29] R. Bhattacharyya, C. Floerkemeier, and S. Sarma, "Rfid tag antenna based sensing: Does your beverage glass need a refill?" in *Proc. IEEE Int RFID Conf*, 2010, pp. 126–133.