Self-sensing passive RFID tags

Gaetano Marrocco
University of Roma Tor Vergata, Via del Politecnico,1, 00133 Roma, Italy, marrocco@disp.uniroma2.it

Abstract

This paper proposes a new paradigm of passive Sensor RadioFrequency Identification Devices for applications in the context of Wireless Sensor Networks. The new tags family works in the UHF band and it is able to detect the value or the change of a tagged body's feature without using any specific sensor. The system is provided with multiple chips placed on a cluster of antennas or onto a single multi-port antenna, and exploits the natural mismatching of an antenna's input impedance with respect to a change of the target where it is placed.

1. Introduction

The recent advances in Wireless Sensor Networks (WSNs) [1] for applications in mobile and time-varying environments, are generating a growing attention to low-cost and low-power wireless nodes equipped with radio and sensing ability and spatially distributed to ensure a cooperative monitoring of physical or application-specific conditions and parameters. Typical fields of applications for WSNs include environmental and habitat monitoring, disaster relief [2], health care, inventory tracking and industrial processing monitoring, security and military surveillance, smart spaces applications. A novel technological trend is the integration among wireless sensor networks and Radio Frequency IDentification (RFID) technologies. Such a convergence of sensing and identification technologies may enable a wide range of heterogeneous applications which demand a tight synergy between detection and tagging. Recently, a variety of projects implementing sensor enhanced RFID systems has been presented for the monitoring of objects and humans [3], the automatic products tamper detection and the identification of harmful agents.

Up to date, several approaches have been proposed to provide RFID devices with enhanced sensing and detection capabilities. The main approaches make use of active or passive RFID transponders and Surface Acoustic Wave (SAW) devices [4]. A significant example of enhanced passive RFID system is given by the Wireless Identification Sensing Platform (WISP) project [5] which introduced the concept of ID modulation making use of inertial switches and enhanced power harvesting units to mechanically toggle between two commercial RFID integrated circuits.

Within this scenario, this paper proposes an investigation on a new paradigm for passive Sensor RFIDs in the UHF ISM band, able to detect the value or the change of the tagged body's features without any a-priori knowledge about the object position and orientation with respect to the querying device. The considered tags family may work without any specific embedded sensor since it exploits the 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 case undergo a mismatching and produce a change of the read distance. The variation of back-scattered power corresponding to the impedance mismatching can be thus detected by the reader (Fig.1). 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 back-scattered signals are originated. Each of them is labeled by the unique identification code (ID) of the responding IC. These data may be available for post-processing at the interrogating device with the purpose to detect some target's features or their modification along with the time

2. Basic Definitions for RFID Systems

Since the proposed RFID platform is deeply based on the dependence of the RFID system parameters on the tagged object's features, the basic definitions are now quickly reviewed in a unitary context.

At the beginning of the reader-to-tag communication protocol [6], the reader first *activates* the tag, placed over a target object, by sending a continuous wave which, by charging an internal capacitor, provides the required energy to perform actions. During this *listening mode*, the microchip exhibits an input impedance $Z_{chip} = R_{chip} + jX_{chip}$, with X_{chip} capacitive, and the antenna impedance $Z_A = R_A + jX_A$ should be matched to Z_{chip} ($Z_A = Z^*_{chip}$) for maximum power transfer. The maximum fraction $P_{R\to T}$ of the reader input power that is absorbed by the tag is

$$P_{R\to T} = \left(\frac{\lambda_0}{4\pi d}\right)^2 G_R \tau G_T P_{in}, \qquad \tau = \frac{4R_{chip}R_A}{\left|Z_{chip} + Z_A\right|^2} \tag{1}$$

where λ_0 is the free-space wavelength, d is the reader-tag distance, G_R is the gain of the reader antenna and G_T is the gain of the tag over the target, having assumed polarization-matched antennas aligned for maximum directional radiation. τ is the power transmission coefficient. The tag is activated when the absorbed power exceeds the tag's microchip sensitivity threshold: $P_{R\to T} > p_T$. During the next steps of the communication, the tag receives the command coming from the reader and it finally sends back the data through a back-scattered modulation of the continuous wave coming from the reader itself. The tag's IC acts as a programmable switching device which toggles between a low or high impedance Z_{mod} . During the data transfer, the RFID system can be considered as a monostatic radar and therefore it can be characterized by the radar range equation which, for the case of typical RFID tags, can be expressed [6] in the form

$$\frac{P_{R\leftarrow T}(d)}{P_{in}} = \left(\frac{\lambda_0}{4\pi d}\right)^4 G_R^2 G_T^2 \rho, \qquad \rho = \frac{4R_A^2}{\left|Z_{\text{mod}} + Z_A\right|^2} \tag{2}$$

where $P_{R\leftarrow T}$ is the power received back by the reader and ρ is a modulation parameter related to the tag's radar cross section.

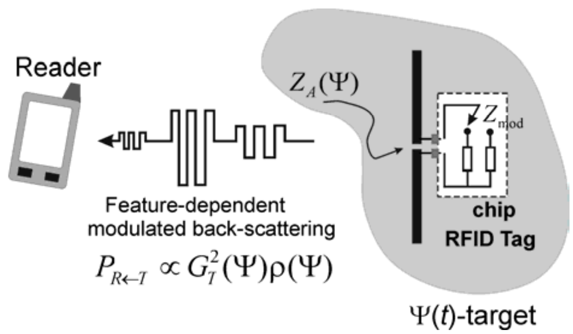

Fig.1: Reader-tag scenario wherein the change of the target's features may produce a modulation of the backscattered power signal.

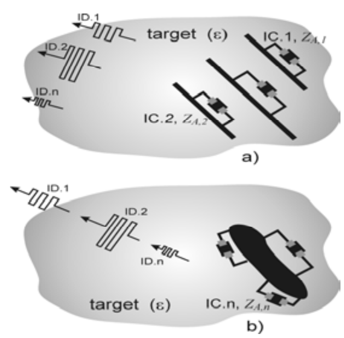

Fig.2: Multi-port tag systems: a) a cluster of co-located single-port tags; b) a single multi-port tag provided with multiple chips

3. The multi-port tag concept

Like any antenna immersed or located close to a real object, the input and radiation characteristics of a passive RFID transponder placed on a target, as well as the strength of the back-scattered power, are closely related to the physical properties of the tagged object itself, e.g. on its constitutive material, shape, temperature, humidity or other. We denote with $\boldsymbol{\Psi}$ the set of the relevant target's features which could undergo changes along with the time, or have to be monitored in someway. If the tag antenna has been designed for optimal performances when placed on a target with nominal set of features Ψ_T, e.g. such that the antenna impedance $Z_A(\boldsymbol{\Psi}_T)$ equals in this condition Z^*_{chip}, a change of one or more target's parameters with respect to $\mathbf{\Psi}_T$ may produce a variation of the input impedance and hence the mismatch $Z_A \neq Z^*_{chip}$. Accordingly, also the back-scattered power collected at the reader port will be modified. In the limiting case, the tag may be completely mismatched so that $P_{R \to T} < p_T$ and the tag is therefore inactive. For the sake of clarity, let us focus on the simplified case for which a single target's feature is subjected to change, and such a parameter be the relative dielectric permittivity (simply permittivity ε in the following). It is now useful to define the tag's Activation Set $A_\varepsilon(d)$ for a link length d, as the set of target's permittivity values for which the power harvested by the tag is enough to activate it: $A(d) = \{\varepsilon \mid P_{R \to T}(d, \varepsilon) \geq p_T\}$.

As suggested by Eq.2, if the reader-tag distance were known, the change in the target permittivity could be theoretically detected by monitoring the power back-scattered by the transponder. Nevertheless, a single received data is not adequate to retrieve permittivity information in case of moving objects, or in applications in which the distance and the orientation of the tag with respect to the reader are not a-priori known (non-cooperative targets). To overcome these uncertainties, multiple independent back-scattered signals have to be collected by the reader**.** In the proposed platform, these signals are originated (Fig.2) from either a *cluster* of N tags co-located onto a same target, or from a single tag provided with N input ports under the condition that each port or antenna has a different input impedance. In particular, we denote with $G_{T,n}$ the radiation gain when only the *n*th port is fed and the others are closed to a reference load, and with $Z_{A,n}$ the input impedance at the n th port in the same conditions**.**

The multi-port system has to be designed so that, having fixed a target geometry and having chosen N different *reference permittivities* $\{\varepsilon_1, \varepsilon_2, \, .. \, , \varepsilon_N\}$, the n th port impedance is matched to the microchip if the target's permittivity value is ε_n (e.g. $Z_{A,n}(\varepsilon_n) = Z^*_{chip}$). It means that, when the multi-chip system is placed on a real target, the ports will be differently mismatched ($Z_{A,n}(\varepsilon) \neq Z^*_{chip}$) and therefore they will originate independent back-scattered power signals, all of them carrying information about the target's permittivity. The resulting overall object is a *multi-port Sensor* RFID (S-RFID) *tag* that employs the same fabrication technology as the conventional RFID tags but, as shown later on, adds specific sensing capabilities to the typical identification features.

4 Sensing the target's permittivity

Depending on the link length d and on the particular design of the multi-port S-RFID tag, there will exist ranges of the target's permittivity for which either multiple ICs respond (overlapping of Active Sets) and hence the reader is able to collect multiple backscattered signals, or only a port is at most activated and the reader may receive a single ID. Two different sensing modes can be correspondingly achieved: *analog sensing* (multiple responding ICs) and *discrete sensing* or *classification* (single responding IC). For both the cases, it is useful to introduce the *Sensing range* $\mathbf{S}(d)$ of the multi-port S-RFID tag**,** as *the set of all the possible values of the target's permittivity which could be detected, in some way, at a distance* d. Only the analog sensing capability is here described.

If the tag has been designed for close reference permittivities $\{\ \varepsilon_n\ \}$, the port impedances will have similar (but not identical) power transmission coefficients τ_n so that multiple microchips will be turned on. In this case the multi-port system will have overlapped Activation Sets $A^{(n)}$. For any couplet of back-scattered signals received by the reader, each with a different modulation parameter $\rho_n(\varepsilon)$, it is possible to drop out the unknown reader-tag distance by calculating the *backscattered power ratio* $p_{i,j}$ between the received powers in Eq.2,

$$p_{i,j}(\theta, \phi, \varepsilon) = \frac{P_{R \leftarrow T,i}(d, \varepsilon)}{P_{R \leftarrow T,j}(d, \varepsilon)} = \left[\frac{G_{T,i}(\theta, \phi, \varepsilon)}{G_{T,j}(\theta, \phi, \varepsilon)}\right]^2 \frac{\rho_i(\varepsilon)}{\rho_j(\varepsilon)} \tag{3}$$

However, $p_{i,j}$ 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 condition of proportional gain patterns, e.g. such that

$G_{T,i}(\theta,\phi,\varepsilon)/G_{T,j}(\theta,\phi,\varepsilon) = f(\varepsilon)$. This condition could be roughly satisfied considering a cluster of two antennas having a similar geometry.

The retrieval procedure is now described by means of an example involving a two-port system, e.g. able to backscatter two different IDs toward the reader. An overlapping configuration between the activation ranges is illustrated in Fig.3. When both the ID_1 and the ID_2 are received by the reader, the unknown target dielectric permittivity ε_T will belong to the intersection of the two activation regions, e.g. $\varepsilon_T \in [A_1 \cap A_2]$, and therefore the p_{12} ratio can be calculated as in Eq.3. The value of the target's permittivity is hence retrieved by using a *calibration curve* $\varepsilon(p_{12})$ which associates to the actual backscattered power ratio, measured by the reader, a permittivity value for the target (Fig.4). Such a $p_{12} \to \varepsilon_T$ relationship is specific for the particular application, e.g. for a particular class (geometry) of targets and needs to be produced off-line through measurements or numerical simulations on simplified, or well representative, target models by operating a sweep of the parameter under observation and calculating the resulting backscattered power ratio. The application of such a technique therefore requires preliminary electromagnetic processing to produce calibration curves for the specific class of objects and the so obtained database, together with the retrieval procedure, have to be embedded in the reader's (post)processing unit. The S-RFID range $\mathbf{S}(d)$ is given by the merging of the Activation Sets shared by couplets of ports: $S(d) = A_m(d) \cap A_n(d)$.

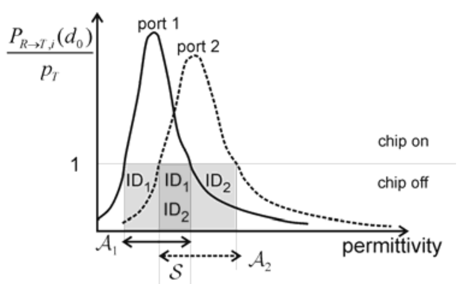

Fig.3: typical Activation Sets, and Sensing Range, of a two-ports RFID tag, designed to work in analog-sensing mode.

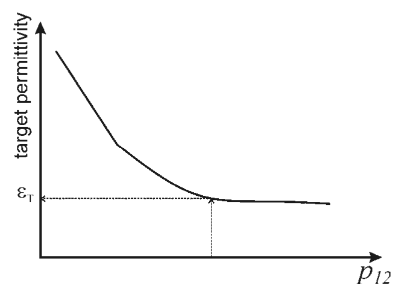

Fig.4: Example of calibration curves $\varepsilon(p_{ij})$ associating the measured backscattered power ratio to a target's permittivity value.

The proposed platform could find application in many security and industrial contexts, for instance i) to monitor (non metallic) container filled with low-loss liquids which could undergo changes along with the time, ii) to sense the filling percentage of a container, iii) to monitor the opening or the tampering of a case also in consideration that the target history could be stored by the reader in the rewritable memory of the tag's microchip.

5. References

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