Passive RFID Couplets as Wireless Interface for Sensor Applications

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***Abstract*—RFID tags are renowned for their versatility and low cost. In recent years, applications making use of them are growing in number and maturity level, but still lack in combining both communication and sensing optimal performance. The present work shows how to use a two-port RFID grid (e.g. a couplet of electromagnetically coupled RFID tags) as a general transducer of sensor information, able to transform a variation of the impedance of a load to which it is connected into a remotely-readable phase variation: in such a way, the tags are effectively turned into a wireless interface for the variable load sensor and are moreover able to provide constant antenna matching and hence stable read range.**

***Index Terms*—RFID, Array, mutual coupling, sensors, wireless communications, SHM**

I. INTRODUCTION

RFID tags promise to be the enabling factor for the upcoming Internet of Things (IOT), where objects and sensors will be connected globally [1]. Several works have for instance shown different ways to turn RFID tags into sensors [2]. Up to now, however, whenever connecting a sensor to a passive tag, sensing could be achieved mostly at expenses of antenna matching, e.g. [3] or [4]. However, the authors have recently demonstrated that, by means of couplets of RFID tags (i.e. two-port RFID systems made of two e.m. coupled tags) and by measuring the phase of such tags, it could be possible to combine requirements on both communication and sensing [5]. In the present paper, therefore, the scenario when a (lumped) sensor with a variable impedance has to be connected to a RFID tag is taken into consideration. The aim is to investigate the phase variation of a RFID tag in couplet configuration, when one tag (i.e. one port of the two-port system) is loaded with the microchip and the other with a generic variable load. Such investigation has clear sensoric applications, as the variable load could be a sensor changing its impedance due to changes of the analyte. Moreover, by using phase information and exploiting the benefit of having mutliple tags, a trade off between communication and sensing capabilities can be reached, thus enabling stable read ranges.

The paper is divided as follows: Sec. II provides the analysis of the problem, with an analytical description showing the behaviour of communication and sensing parameters in function of the variable load; Sec. III provides a preliminary numerical and experimental validation, by simulating an optimized RFID couplet and testing it in real-life.

II. ANALYSIS

A. E.M. Theory of Phase response of couplet of tags

The signal (and the corresponding phase) due to the antenna mode of two coupled RFID tags can be expressed in terms of impedance matrix and chip impedance as in [5]. For hypothesis, the two tags are placed close to each other and at a given *fixed* mutual distance. Tag n is loaded with a UHF microchip, while tag m is terminated on a load, variable according for instance to some sensing function. In this case, the signal received at the reader due to the antenna mode can be rewritten as

$$V_{R,(n)}^{ON/OFF} = \frac{Z_{nn} + Z_{mm} - 2Z_{mn} + Z_L(\Psi) + Z_{Cn}^{ON/OFF}}{\left(Z_{nn} + Z_{Cn}^{ON/OFF}\right)(Z_{mm} + Z_L(\Psi)) - Z_{mn}^2} f\left(r_n\right) \tag{1}$$

where Z_{mn} $\{m, n = 1, 2\}$ are respectively self $(m = n)$ and mutual $(m \neq n)$ impedances, $Z_{Cn}^{ON/OFF}$ and $Z_L(\Psi) = R_L(\Psi) + jX_L(\Psi)$ are the chip impedance in the two ON and OFF states and the load impedance on port m, with Ψ the analyte, i.e. the parameter to monitor. $f\left(r_n\right)$ is a function whose phase only depends on the reader-to-tags distance r_n and on the effective heights of tags and reader.

$$f(r_n) \propto \frac{\lambda^2}{\pi^2}\sqrt{P_{in}R_R^{rad}}/2G_R R_n^{rad} G_n(\underline{\hat{h}}_n \cdot \underline{\hat{h}}_R)^2 \frac{e^{-j2kr_n}}{4r_n^2} \tag{2}$$

The phase measured by the RFID reader can hence be written as [5]:

$$\varphi_n[Z_L(\Psi)] = \tag{3}$$

$$= arg\{V_{R,(n)}^{OFF}[Z_L(\Psi)] - V_{R,(n)}^{ON}[Z_L(\Psi)]\}$$

where the dependence from $Z_L(\Psi)$ has been made clear.

Being the effective heigth for port n defined when port m is in open circuit, it does not depend on the load of port m and $\varphi_0 = arg\{f(r_n)\}$ can therefore be considered as a constant with respect to variations of $Z_L(\Psi)$.

If, for simplicity, it is assumed that the tags are the same and in a symmetric configuration, we have that $Z_{11} = Z_{22} = Z_S$ and $Z_{21} = Z_M$. Phase can hence be written as

$$\varphi_n[Z_L(\Psi)] = \tag{4}$$

$$= arg\{-\frac{2Z_S - 2Z_M + Z_L(\Psi) + Z_{Cn}^{OFF}}{\left(Z_S + Z_{Cn}^{OFF}\right)\left(Z_S + Z_L(\Psi)\right) - Z_M^2} +$$

$$+\frac{2Z_S - 2Z_M + Z_L(\Psi) + Z_{Cn}^{ON}}{\left(Z_S + Z_{Cn}^{ON}\right)\left(Z_S + Z_L(\Psi)\right) - Z_M^2}\} + \varphi_0$$

If the measurement setup (i.e. the distance and orientation between reader and tags) is kept fixed along with the sensing process, φ_0 will be constant (as it only depends on OC parameters and on the distance between reader and tag). The variations of the phase will then be due only to variations of $Z_L(\Psi)$ and hence information on such variations will be remotely retrievable by measuring the phase of the tag as received by the reader.

On the other hand, communication properties are controlled through the realized gain, which has the following expression:

$$\widetilde{G_n}[Z_L(\Psi)] = G_n \chi_n \widetilde{\tau_n} = \tag{5}$$

$$= G_n 4 R_{Cn}^{ON} R_S^{rad} \left| \frac{Z_S - Z_M + Z_L(\Psi)}{\left(Z_S + Z_{Cn}^{ON}\right)\left(Z_S + Z_L(\Psi)\right) - Z_M^2} \right|^2 \chi_n$$

Therefore, also the realized gain depends on the (variable) load of port m. It is interesting to highlight that, being the tags at a fixed distance, G_n and χ_n will be costant and, due to their definition through open circuit of port m, won't depend on its variable load. The depedence of the realized gain from $Z_L(\Psi)$ is thus fully included in the coupled power tranmission coefficient $\widetilde{\tau_n}$.

It is possible to optimize the behaviour of phase and $\widetilde{\tau_n}$ with respect to the load impedance, so that the variation of the load will not compromise the communication capability of the tags (i.e. $\widetilde{\tau_n}$ will stay relatively stable and its value will be close to or even higher [1] than 0dB), and at the same time enable a strong phase variation, allowing for good sensing-related sensitivity. The optimization constraints can be formally expressed as

$$\begin{cases} \Delta\varphi_n(Z_L(\Psi_{max})) - \Delta\varphi_n(Z_L(\Psi_{min})) \geq \Delta\varphi_{n,min} \\ \widetilde{\tau_n}(\Psi) \geq \widetilde{\tau}_{n,min} \end{cases} \tag{6}$$

$$\forall n,\ \forall \Psi \epsilon [\Psi_{min}; \Psi_{max}]$$

By choosing suitable geometrical parameters of the couplet (for instance, a and b from Fig. 1) as degrees of freedom for the optimization, it is possible to find optimal values for them so that the above constraints are met.

A further explanation of the methodology will be shown during the conference.

III. Numerical and Experimental Validation

A. Numerical Simulation

The two coupled T-match dipole antennas proposed in [5] and shown in Fig. 1 will be here used to investigate the behaviour of phase and power transmission coefficient when one antenna is terminated with a variable load. They are etched on a FR-4 plate with a thickness of 0.8 mm: moreover, a wooden plate with a thickness of 3 cm below them is included in the e.m. simulation, to take into account the effect of the wooden desk used during experimentation (see next Subsection).

An NXP G2XM chip is connected to one port of the couplet, while the variable load $Z_L(\Psi)$ is connected to the other port. For the present experimentation, it will be assumed that the load has a variable reactance, hence being $Z_L(\Psi) = R_L + jX_L(\Psi)$. Let's for instance assume that it is required to optimize the antenna couplet to operate in the region X_L=[-120;-200] Ohm (with a fixed $R_L = 5\,\Omega$).

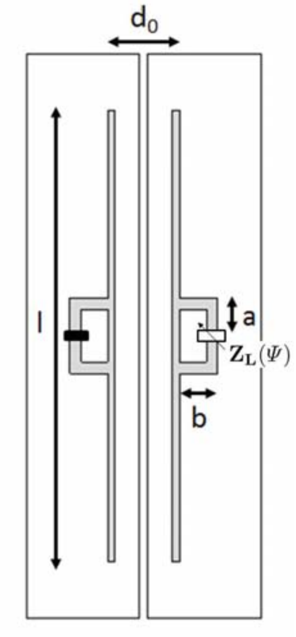

Figure 1. Dipole antennas with T-match circuit used for the validation of the formulas (from [5])

This could be for instance the case when a capacitive sensor is attached to the RFID couplet and its reactance varies between 0.9 and 1.5 pF, as for instance reported for the sensors in [7] and [8]. By proper optimization of the antenna couplet geometrical parameters, it is possible to obtain a $\widetilde{\tau_n}$ and φ_n behaviour best suited for this load impedance variation, as shown in Fig. 2.

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[1] Due to the mutual electromagnetic interaction, RFID grids can have $\widetilde{\tau_n}$ values higher than 0 dB, as first shown in [6]

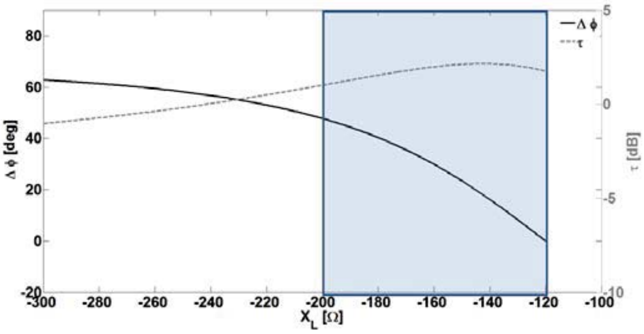

Figure 2. φ and $\widetilde{\tau_n}$ versus X_L for the simulated dipole antenna couplet ($Z_C^{ON} = 16 - j156$ and $Z_C^{OFF} \sim 150$ at f_{RFID})

In the impedance range $X_L = [-300; -100]$, two different regions can be observed: for $X_L < -200\ \Omega$, phase variation is limited and the power transmission coefficient is not very high. On the other hand, when $X_L > -200\ \Omega$, i.e. in the required operation region (blue area in Fig. 2), the phase decreases steadily along with X_L ($\triangle\varphi = 49°$ for X_L =[-120;-200] Ohm), while $\widetilde{\tau_n}$ achieves better values ($\widetilde{\tau_n}$>1dB in X_L=[-120;-200] Ohm) , hence permitting optimal communication between the reader and the RFID couplet. This optimized solution will be used for real-life testing.

B. Laboratory Experimentation

The RFID couplet system simulated in the former Subsection has been manufactured and tested in laboratory environment (Fig. 3). In order to have a controlled variable reactance, a voltage-controlled varactor has been used and connected between the terminals of one dipole, in series with a low-value resistor, as to obtain the $Z_L = 5 + jX_L$ load impedance, with X_L=[-100;-300] Ohm, as shown in Fig. 4. An external voltage generator was connected to the varactor in order to steer its reactance.

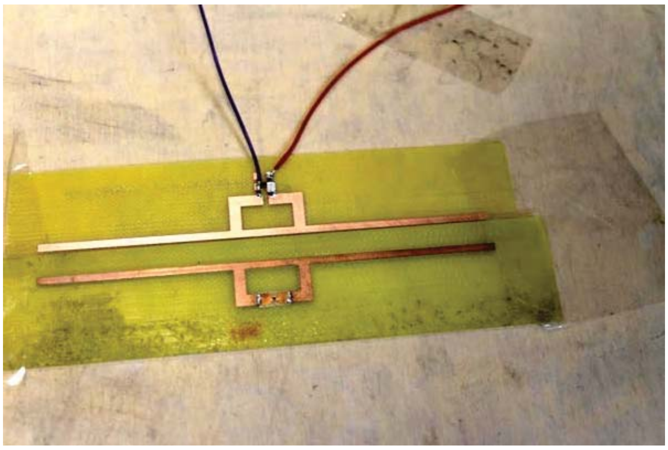

Figure 3. Prototypes manufacted on a FR-4 plate and placed over a laboratory wooden desk for testing. The variable reactance is obtained with the help of a voltage-controlled varactor

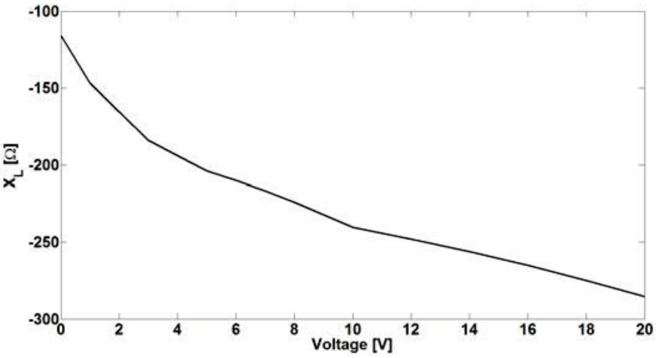

Figure 4. Reactance of the varactor versus voltage supplied by the external voltage generator

The tags have been placed over a wooden desk and interrogated through a Thingmagic M6 reader [9], connected to a 6-dBi linearly polarized antenna, placed at a distance of 90 cm above the desk. Phase and turn-on values (useful to calculate the measured realized gain as in [10]) have been collected from the RFID reader, along with voltage values of the voltage generator (which determine the X_L of the load). The measured $\widetilde{G_n} = G\widetilde{\tau_n}$ and φ_n with respect to the load reactance are shown in Fig. 5, together with the simulated results for comparison purpose.

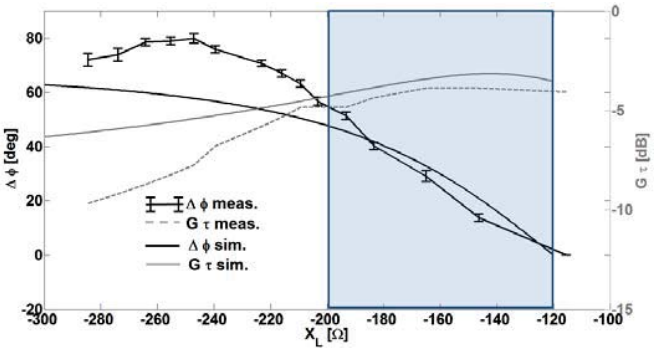

Figure 5. Measured φ and $\widetilde{G_n}$ versus X_L for the manufactured dipole antenna couplet (at $f_{RFID} = 867$ MHz)

The measured values are in good agreement with simulation and show how good phase sensitivity and stable communication (i.e. stable $\widetilde{G_n}$) can be obtained in the required operation range (blue area in Fig. 5). Further experiments with real-life sensors will be shown during the conference.

IV. CONCLUSION

The behaviour of phase and realized gain of a couplet of RFID tags with respect to a variable load connected to one port of the couplet has been demonstrated. It has been shown that it is possible to optimize the behaviour of such couplets, such as to obtain optimal performance for a given impedance range of the variable load, both in terms of communication and sensing. A first example has been provided to validate the theory. Further laboratory experiments will be shown at the conference.

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