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RFID-Based Reconfigurable Intelligent Surfaces: towards Wireless and Ultra-Low-Power Reconfigurability

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Abstract

Reconfigurable Intelligent Surfaces (RISs) are emerging as a revolutionary technology since they allow the artificial control of the wireless propagation environment aiming to enhance the coverage, reliability, and spectral efficiency of future wireless communications. RIS are smart surfaces composed of several tunable unit cells that require costly and power-hungry hardware platforms, as well as physical wires, to be reprogrammed. To overcome these limitations, in this paper we propose Radio Frequency Identification (RFID) technology as a potential alternative, since it is a low-cost and low-power solution able to provide wireless connectivity. The proposed architecture aims to exploit RFID tags as wireless controllers for RIS unit cells since they are programmable and capable to act as DC power sources for external devices. We will demonstrate the proposed approach by means of two examples: ID modulation of a 2-elements RFID grid and pattern reconfiguration of a 3-elements antenna array. Further studies will be carried out exploiting passive RFID controllers working in a wider frequency range.

1 Introduction

In recent years, Reconfigurable Intelligent Surfaces (RISs) are emerging as a revolutionary technology since they allow the artificial control of the wireless propagation environment with the aim to enhance the coverage, reliability, and spectral efficiency of future 6G wireless communications [1]. RISs are artificial and smart surfaces, typically comprising several sub-wavelength elements (unit cells) whose scattering properties can be dynamically adjusted (programmed) to modify, in amplitude and phase, an Electromagnetic (EM) wave impinging the surface (typically coming from a transmitter) in order to reflect the signal in defined directions, avoiding obstacles and enhancing the coverage (Fig. 1).

Several tuning mechanisms have been proposed by researchers [2], but currently the most reliable and commonly used is the electrical one [3], in which the unit cell is equipped with electrically tunable components such as PIN or varactor diodes. By properly adjusting the bias voltage of each cell by means of hardware platforms, e.g., Field Programmable Gate Arrays (FPGAs), a change in the state of the tunable component can be induced, resulting in the modification of the unit cell scattering properties. Even if the electrical tuning is a fast, effective, and reliable solution, the main issues are related to the power needed to power the hardware platforms and the physical wires required for reprogramming [4]. Therefore, exploring alternative tuning mechanisms (e.g., material-based, optical, or mechanical, etc. [5]) with the aim to supply and reprogram RISs in a more efficiently and cost-effective way is essential.

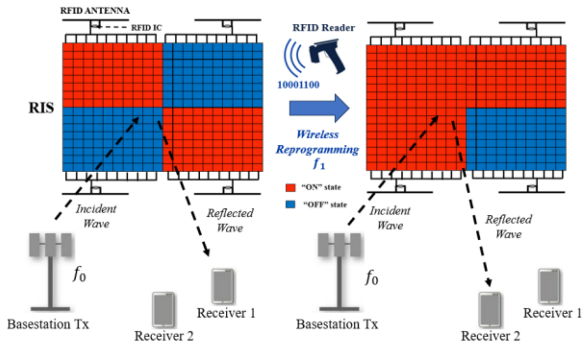

Figure 1. Concept of RFID-Based RIS. The incident wave is initially redirected through receiver 1. Consequently to a reconfiguration by means of an RFID reader, the wave is instead redirected through receiver 2. Frequency f_0 is for the generic unmodulated field, while f_1 is in the RFID UHF-Band.

To this purpose, in this paper we describe how the Radio Frequency Identification (RFID) technology can be a potential alternative, since it is a low-cost and low-power solution capable to provide wireless connectivity together with simple and miniaturized devices [6]. A similar idea was also investigated in [7]. The proposed architecture aims to exploit RFID tags as wireless controllers for RIS unit cells (Fig. 1). The rationale is that the latest generation RFID Integrated Circuits (ICs) are *programmable* and have the capability to act as DC power supply for external devices. More specifically, they can be programmed to execute a predetermined command subsequently to a particular event such as, for instance, the availability of a compatible (in terms of frequency and power) RF field. Thus, taking advantage of the DC voltage delivered by the IC, a RF switch can be set in high (1) or low (0) state, resulting in a *1-bit reconfigurability*. The IC will also remember the command because it is also capable to store instructions in its *user memory*, which is writeable and non-volatile [8]. Hence, once activated through an impinging field, programmable RF switches could selectively connect one or more conductive elements properly designed, such as unit cells of an array or portions of a single radiating structure. Even if this alternative solution is probably less performant than the traditional and active ones, it is more sustainable, with zero environmental impact, and usable in

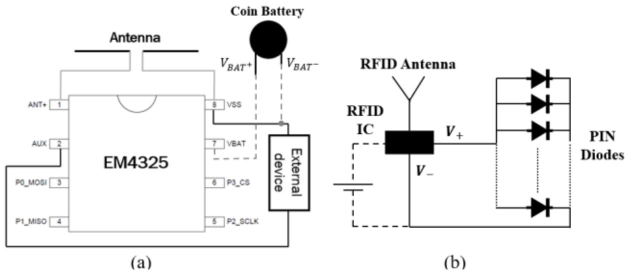

Figure 2. (a) Pin layout of the EM4325 IC, working in BAP mode. (b) Circuit schematic of an RFID-based RIS where each diode ideally is a unit cell.

all those contexts where batteries or external power supplies are not allowed (embedded systems and sensors).

The paper is organized as follows: in Section 2, we will provide a detailed description of the proposed system and then we demonstrate the feasibility of the approach in Section 3 through two application examples. In the first one, we demonstrate the selective activation of a sector of a 2-elements RFID grid to enable an ID (i.e., the unique identification number assigned to all RFID ICs [8]) modulation of the elementary unit of the grid. In the second case, we modify the radiation pattern of a 3-elements array to selectively choose directive or omnidirectional radiation modes.

2 System Description

The proposed system is conceived to work as illustrated in Fig. 1. Considering an array of *n* x *m* unit cells, the idea is to divide it in *n* sub-arrays, each composed by *m* elements, and to control each of them by means of a RFID tag, operating at Ultra-High Frequencies (UHF). What happens is that, when a compatible (in terms of frequency and power) RF-field at frequency f_0 impinges the surface, each RFID IC will wake-up and starts to drive the RF switch to which it is connected. It is worth noticing that the field does not need to be modulated (as it is in typical RFID systems), meaning that the power needed to supply the RIS can be provided from alternative sources, such as the ambient backscattering or from the EM wave that the RIS needs to modify. Moreover, the state of each unit cell can be set many times by reprogramming each IC wirelessly (up to tens of meters) through an RFID reader at frequency f_1.

Concerning the suitable RFID ICs, to the best of our knowledge, there are two commercially available ICs, that are the EM4325 [9] and EM4152 [10] providing the previous described features. The first one operates in Battery Assisted Passive (BAP) mode, meaning that its waking-up depends only on the *AUX event* (i.e., the availability of a compatible RF-field) occurrence or not, since the power needed to turn on the IC and eventually supply an external device is delivered by the battery ($V_{max}^{DC} = 3.3\,V,\ I_{max}^{DC} = 10\,mA$) through the *AUX pin* (Fig. 2a). The EM4152, on the other hand, is a completely passive IC, so that it could allow to realize a passive RIS which will collect the power directly from the incoming wave. Since we want to provide a proof-of-concept, in the following we will consider the EM4325 IC (whose pin layout is shown in Fig. 2a) because it works in BAP mode and therefore permits to easily drive an external device. The IC impedance is $Z_{chip} = 7.6 - j114\ \Omega$ and the power sensitivity (i.e., the minimum power required to make the IC respond to an EPC GEN2 command) is $p_c = -28\ dBm$ in BAP mode. According to Fig. 2b, the programmable RF-switches must be connected in parallel to the AUX pin.

The wireless reconfiguration is achieved by instructing the IC to deliver a DC voltage when the AUX event happens (state-0: AUX pin disabled; state-1: AUX pin enabled). This command remains stored in the IC memory even if the IC is turned off, maintaining the RIS in the current configuration until a new reprogramming occurs. To resume, the system works following two steps:

1. *Programming:* The desired IC status (1 or 0) must be stored in the user memory, together with the AUX event. RFID Gen2 Protocol [8] must be used.
2. *Activation:* When the IC is illuminated by a compatible RF source, it will deliver or not a DC voltage, depending on the state.

3 Application Examples

3.1 ID Modulation

Every RFID IC is characterized by a unique identification number (ID) which is required to be sent to the RFID reader (after a query command) to initiate the communication. Once the reader receives the expected ID, it will be able to send specific EPC GEN2 commands or to collect the data sensed by the IC. The capability of the IC to receive the query and respond to it with his EPC depends on the quality of the RFID tag design, which is given by the *realized gain* G_τ, i.e., the *gain G* of the antenna scaled by the *power transfer coefficient* τ, which accounts for the impedance mismatch between the antenna and the IC [11]:

$$G_\tau = G \cdot \tau, \tag{1}$$

where

$$\tau = \frac{R_{IC} R_A^{in}}{\left|Z_{IC} + Z_A^{in}\right|^2} \leq 1. \tag{2}$$

In (2), the term $Z_A^{in} = R_A^{in} + jX_A^{in}$ is the antenna impedance while $Z_{IC} = R_{IC} + jX_{IC}$ is the IC complex impedance. Therefore, the idea is to induce a strong variation of the current flowing through the IC, as well as of the impedance seen by the IC itself (Z_A^{in}), by changing the status of a RF-switch placed in proximity of the IC. Consequently, it will respond or not depending on the switch state. This approach was previously investigated in [12], where a 2-elements RFID antennas grid (Fig. 3) was designed and tested to perform ID modulation. The system consisted of two dipoles, orthogonally arranged for coupling minimization purposes, which are physically connected. The first one was equipped with the EM4325 IC, while the

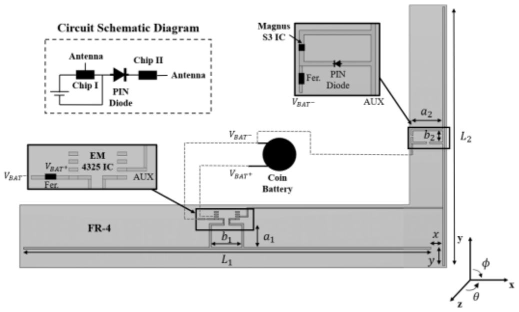

Figure 3. Schematic layout of the 2-elements RFID antennas grid capable to perform ID modulation.

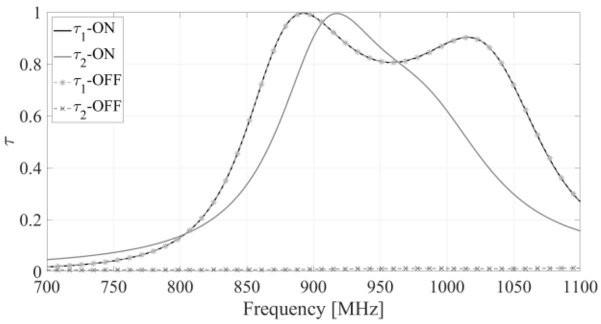

Figure 4. Simulated (a) power transfer coefficients τ, and (b) realized gains G_τ; for the two antennas in ON and OFF state.

second one integrated a Magnus S3 IC ($Z_{chip} = 7.6 - j114\,\Omega$, $p_c = -16$ dBm) [13]. Both the antenna impedances were matched to the respective IC impedance by means of a T-match [11]. The ID modulation was achieved by properly programming the EM4325 IC in the two possible states by adjusting the bias voltage of a PIN diode connected on the T-match of the S3 IC. When the PIN diode was ON (state 1), the impedance matching was achieved, while when it switched in its OFF state (state 0) a drastic change in the impedance Z_A^{in} occurred, causing the S3 IC to stop responding. This concept is illustrated in Fig. 4, where it is highlighted that the power transfer coefficient of the S3 IC (τ_2) drastically drops to 0 when the diode switches to the OFF state.

Experimental measurements were also carried out by soldering a blue LED diode across the EM4325 and a red LED diode in parallel to the PIN diode (Fig. 5). LED diodes light up as a result of the presence of an *unmodulated* RF-field (in the UHF-Band), while programming is performed with a RFID reader. When The system is in the state 0, only the EM4325 is responding, therefore only the blue diode lights up. On the other hand, after reprogramming in the state 1, the S3 IC starts responding, resulting in the activation of the red diode, too. Further details about the system and measurements results can be found in [12].

3.2 Radiation Pattern Reconfiguration

As a second application example of the proposed RFID-Based programmability, the radiation pattern reconfiguration of a 3-elements antenna array is presented. The array (Fig. 6) has a central active element equipped with the EM4325 IC, while the other two passive elements

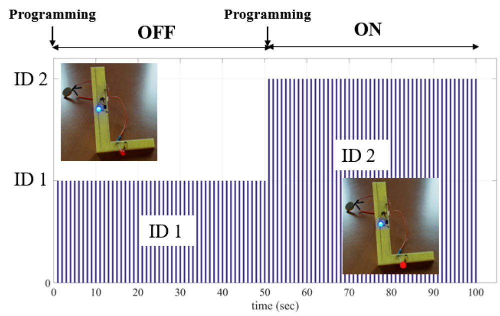

Figure 5. Digital response from tags and LED diodes illumination according to the state of the EM4325 IC.

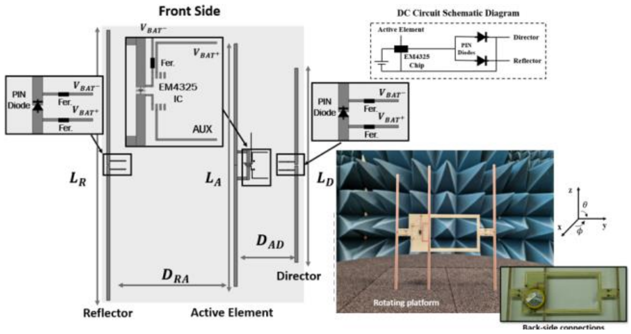

Figure 6. Layout of the 3-elements antenna array. The DC connections are schematized in the upper right, while the realized prototype is in the lower right. Geometrical dimensions are: $L_R = 167\,mm$, $L_A = 150\,mm$, $L_D = 120\,mm$, $D_{RA} = 80\,mm$, $D_{AD} = 38\,mm$.

are equipped with PIN diodes for reconfiguration purposes. The bias voltage is provided by the AUX pin of the EM4325 to which each PIN diode is connected via ferrite beads for DC decoupling purposes. Finally, the battery was placed on the back side. Simulation was performed in CST Microwave Studio 2023 and the PIN diodes were simulated considering their .s2p files [14]. The geometrical parameters, i.e., lengths of passive and active elements as well as their mutual distances were chosen as the result of a parametric analysis oriented to the optimization of the realized gain G_τ.

A prototype of the array on an FR-4 substrate ($\varepsilon_r = 4.3$, $tan\delta = 0.02$) was realized for radiation pattern measurements purposes. The prototype was placed on a rotating platform and the IC was interrogated by a circularly polarized reader antenna (patch with broadside gain $G_R = 7.5\,dBic$) placed 60 cm away and connected to the TagFormance UHF Pro station. The resulting radiation patterns are showed in Fig. 7a and compared with simulations, showing a very good agreement. In the state 1 (*Yagi mode*) both diodes are ON, hence, they ideally act as short circuits and the typical Yagi-Uda radiation pattern is achieved. Indeed, the array has an *endfire* radiation pattern with a maximum realized gain of 4 dB ($G_\tau^{sim} = 6.6\,dB$) for $\phi = 0°$ and a front-to-back ratio of about 12 dB. On the other hand, when diodes are switched to the OFF state (*dipole mode*), they act similarly to an open circuit, resulting in the array radiation pattern reconfiguration to a "dipole-like" *isotropic* pattern with a realized gain of -4.7 dB ($G_\tau^{sim} = -2.2\,dB$). The rationale is in the weaker currents flowing

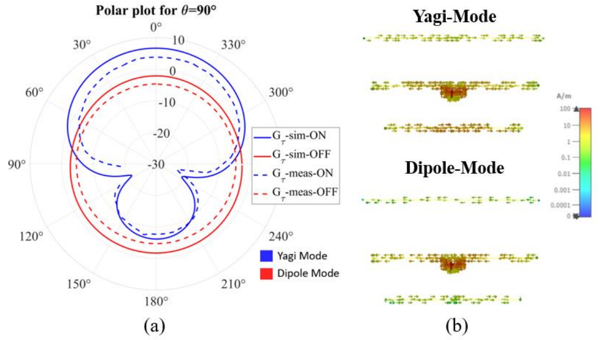

Figure 7. (a) Simulated and measured radiation patterns for the reconfigurable antenna array in the endfire direction for both states. (b) Surface currents (@900MHz) flowing through the three elements in both states.

through the passive elements due to the ideal open circuit induced by the PIN diode (Fig. 7b).

4 Conclusions and Future Works

In this paper the idea of a RFID-based RIS provided with wireless and ultra-low-power programmability was introduced and discussed. The proposed architecture is considerably cheaper with respect to the state-of-the-art programming hardware and does not require any physical wire. Moreover, such a system is more sustainable, with zero environmental impact, and usable with respect to traditional ones, especially in that contexts where batteries or external power supplies are not allowed (embedded systems and sensors). It is worth noticing that, even if in our preliminary analysis we have considered an RFID IC working in BAP mode, which still consumes less power if compared, for instance, with FPGAs (about $0.32\ W$ w.r.t. $6.52\ W$ if considering a 32×16 elements RIS [4]), in future works a completely passive system could be employed. Therefore, further studies will be carried out concerning the possibility to use the EM4152 IC since it would be a game-changer for RIS widespread application. The stability of the output DC voltage needs to be investigated as well, considering that a passive IC will deliver a voltage that depends on the collected RF-field. Moreover, the IC wake-up strongly depends on the received RF-field's frequency and power for both BAP and passive mode. Hence, the RFID antenna must be optimized to work with the widest possible bandwidth. Finally, since the IC impedance is strongly affected by both the incoming wave frequency and power, a detailed characterization of the IC features as a function of the RF-field properties will also be carried out to investigate the feasibility to embed such a system in state-of-the-art RIS (which works in the 5G bands).

The RFID-based reconfigurability can be a valuable solution also in other applications such as the protection against physical and cyber attacks to devices employed in the Healthcare Internet of Things (H-IoT). Indeed, currently there are no RFID ICs that are capable of simultaneously perform cryptographic algorithms and sense physical quantities. Therefore, the ID modulation can be exploited to realize a system in which one IC works as the *"authenticator"* and the other as the *"sensor"*. The idea is that the reader can collect the data stored in the sensor IC only if it is previously authenticated by the authenticator IC. Another possibility is to realize a RFID-Based reconfigurable Frequency Selective Surface (FSS) as a protection system for physical attacks against implantable devices. The concept is that the surface will block any communications with the implanted device until you are not authenticated.

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