RFID-Based Reconfigurable Electromagnetic Devices

Francesco Lestini, Student Member, IEEE, Gaetano Marrocco, Senior Member, IEEE, and Cecilia Occhiuzzi, Member, IEEE

Abstract—Modern wireless communication systems are becoming increasingly necessary, emphasizing the need for electromagnetic devices that can flexibly operate under different conditions, e.g., under power constraints or in hostile environments where scattering objects randomly modify coverage areas and communication links. Due to their ability to dynamically change operating frequency, radiation pattern, bandwidth characteristics, and polarization, reconfigurable objects (especially antennas and backscattering surfaces) have received significant attention in this context. Electromagnetic features can be electronically selected by controlling the bias voltage of tunable elements adequately integrated into the layout. Usually, this is done by employing external programmable controllers that need power sources and wired connections, leading to unusable configurations for several scenarios. Thus, exploring alternative electronic tuning mechanisms becomes essential. This paper proposes RFID-Based Reconfigurable Electromagnetic Devices as a wireless, cost-effective, and low-power solution. The system’s operating principle, potential architectures, and applicability in practical scenarios are presented. Theoretical and experimental analysis validate the proposed architecture, whose capabilities are finally demonstrated by prototyping and testing two reconfigurable antenna arrays.

Index Terms—RFID, reconfigurable devices, remote control, low power consumption.

I. INTRODUCTION

In recent years, the need for advanced wireless communication systems and the rapid expansion of the Internet of Things (IoT) applications have highlighted the necessity for electromagnetic devices that can quickly adapt to a wide range of operating conditions [1], [2]. In this scenario, reconfigurable objects have attracted notable attention due to their ability to dynamically change operating frequency, radiation pattern, polarization behavior, or a combination of them [3]. Examples of reconfigurable devices are stand-alone radiating elements [4], [5], antenna arrays [6], [7], Frequency Selective Surfaces (FSSs) [8], [9], and Reconfigurable Intelligent Surfaces (RISs) [10], [11].

An Electromagnetic (EM) device can be reconfigured by redistributing its surface currents in a controllable way to induce modifications in its fundamental electromagnetic features. This can be done by singularly or jointly exploiting mechanical, all-electronic, material-based, and optical methods [12]. Electrical-based reconfigurability [13] can be achieved by loading the device with electrically tunable components such as PIN diodes, Micro-Electro-Mechanical Systems (MEMS) switches, or varactor diodes, whose bias voltage can be adjusted by using programmable controllers such as Field Programmable Gate Arrays (FPGAs) or Digital Signal Processors (DSPs) [14]–[16]. However, the widespread use of reconfigurable devices is currently prevented by the required power, high cost, and complexity of programmable controllers [17], the need for additional elements such as shift registers, and the physically wired interconnections required to connect the entire reconfiguration network. This is especially a problem for some kinds of applications, like body-worn antennas or devices embedded in buildings, materials, or moving objects [18]–[20], for which wired interconnections are particularly difficult to implement.

In this paper, we propose a wireless reconfiguration architecture based on the Ultra-High-Frequency Radio Frequency Identification (UHF RFID) technology since it is low-cost, low-power, and capable of providing wireless connectivity and basic computational capabilities through simple and miniaturized devices [21]. The rationale for this approach is that the latest generation of RFID Integrated Circuits (ICs) [22], [23] can also act as a DC power supplier for external devices [24], having a DC port whose voltage can be set as a reply of a command sent directly by the reader or stored in their...
internal memory bank [25]. Therefore, the idea is to combine the digital features of the ICs typically embedded in RFID transponders with the analog features of classical electromagnetic devices to provide them with wireless reconfigurability. RFID ICs thus become wireless controllers (Fig. 1), enabling the removal of power supplies, cables, and expensive programmable devices that are required by traditional wired reconfigurable architectures.

The idea to use RFID technology as a reconfigurable platform was preliminary introduced in [26], where authors demonstrated the possibility of assisting a source-destination link by forcing RFID tags composing a RIS to backscatter in carefully selected groups. The control of tags’ behaviour was only at the protocol level, without modifying the layout of the surface. In [27] instead, a preliminary attempt of using tags to control tunable elements embedded into a reflective surface was presented. An 8x8-element information metasurface was introduced, in which RFID tags were used to achieve beam splitting, beamforming, and EM-wave absorption of the surface. The Authors recently presented in [28] an early feasibility evaluation of the proposed approach. An arrangement of two elements operating in the RFID UHF band was configured to turn communication on or off with the external reader selectively. This paper extends these results to describe better architectures, operating principles, possibilities, and limitations concerning real-world applications. For this purpose, the IC performance in different frequency bands is characterized to evaluate the possibility of exploiting the proposed architecture with different electromagnetic sources outside the typical UHF RFID frequency band and, hence, to analyze the usability in supporting other communication platforms and services.

The paper is organized as follows: in Section II, we provide a detailed description of the rationale of the proposed approach, the operative architectures, the potentialities, and the constraints. Section III characterizes the IC programmability features, with particular attention to typical electromagnetic environmental sources, such as LoRa, WiFi, Bluetooth, and sub-S 5G communications. Then, preliminary proofs of the proposed wireless reconfigurability are provided in Section IV through two application examples. In the first, the selective activation of an RFID tag depending on the state of another one is demonstrated. In the second case, the radiation pattern of a 3-elements array is configured to switch between directive and omnidirectional radiation modes.

II. RATIONALE

The principle of the proposed reconfiguration method is sketched in Fig. 2. For clarity, we focus on an electromagnetic object (EM-O) made up of only three conductive elements (namely a, b, c), whose mutual connections are determined by the state of an RF switch \(Z_{ON,OFF}\), adequately controlled by the RFID IC. The described architecture can be easily extended to a generic grid of \(n \times m\) unit cells, integrating one or more RF components \(Z_{i,n,m}^{ON,OFF}\), and adequately controlled by one or more RFID ICs \(i\) (see Fig. 1 again). The resulting structure will be provided with \(i\)-bit reconfigurability since a single RFID IC can control several switches, but not independently.

![Fig. 2. Rationale of the proposed RFID-Based Reconfigurable Electromagnetic Object. The reference layout consists of three conductive elements (a, b, c) properly connected to an RFID IC. The latter controls the state of a tunable element \(Z_{ON,OFF}\) through its DC output ports, thus determining the configuration assumed by the object and its electromagnetic features.](image-url)
TABLE I
FREQUENCIES, FIELDS, AND OPERATION OF THE RECONFIGURABLE EM-O

<table>
<thead>
<tr>
<th>Action</th>
<th>Frequency</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Programming</td>
<td>( f_p )</td>
<td>EPC UHF Gen2 command</td>
</tr>
<tr>
<td>Power-up</td>
<td>( f_s )</td>
<td>Generic modulated/unmodulated signal</td>
</tr>
<tr>
<td>Operation</td>
<td>( f_o )</td>
<td>Operative field of the EM-O</td>
</tr>
</tbody>
</table>

A. Operation and Architectures

Three working conditions can be identified, each with its frequency and required/produced signals as specified in Table I:

1) **Programming:** The desired RF component status \( Z_{\text{ON,OFF}} \) is stored in the IC user memory. The RFID Gen2 protocol [29] must be used.

2) **Power-up:** When a compatible RF source illuminates the IC, it will deliver or not a DC voltage to the connected RF component, depending on the imposed state.

3) **Operation:** While illuminated, the EM-O performs actions according to the imposed configuration.

The power-up and operation phases are dependent and synchronous. Programming can be performed, instead, off-line and repeated several times, depending on the particular application. The RFID-based programmable EM-O is an inherently multi-frequency device, capable of operating at the three different frequencies \( f_p, f_s, f_o \). Two architectures can be envisaged:

1) The ICs are embedded directly in the layout so that the same conductive elements seamlessly do harvest, activation, and operation;

2) Harvest, activation, and operation are demanded to specific layout portions, each tuned to the particular frequency \( f_p, f_s, f_o \). In this perspective, it is possible to properly include in the device Programming and Operating nodes whose relationship can be assumed to be similar to the typical master/slave one.

According to the chosen configuration, the requirements on multi-frequency behavior could be relaxed in case power-up, operation, and programming rely on the same bandwidth/service \( f_s = f_p = f_o \) as it is for systems conceived only for RFID applications.

III. IC Characterization

In the most general case, the power-up and operation frequencies and the signals listed in Table I can differ from those foreseen by the UHF EPC Gen2 protocol. Although some experimental evidence [30] suggested that RFID ICs can also operate in other frequency bands, the nominal features are generally available from the datasheet only in the UHF band. Thus, to evaluate the real possibility of exploiting ambient sources to power-up the reconfigurable device, the power sensitivity \( p_c(f) \) at different frequencies needs to be characterized. Furthermore, to select the most suitable RF switch to be integrated into the layout, the DC power output \( V_{\text{out}} \) must be evaluated regarding absolute values and stability.

To cover the most common ambient sources (listed in Table II), a broadband analysis was conducted within the 0.4 GHz – 5 GHz frequency band through a custom board (Fig. 3.b) implementing the procedure described in [31]. The board connects the IC to a Vector Network Analyzer (VNA) for sensitivity characterization over frequency \( p_c(f) \) and to a digital multimeter for measuring the DC voltage output \( V_{\text{out}} \).

An RF-BalUn [32] was included between the IC RF ports and the VNA for pre-matching and balancing purposes [31] while a 10 kΩ resistor was connected to the output port to perform voltage measurements. After a first calibration phase through a custom Short-Open-Load (SOL) calibration kit, by exploiting the wired turn-on method [33], VNA measures the reflection coefficient \( S_{11} \) when it feeds the IC at different frequencies with increasing power \( P_{\text{VNA}} \). The amount of power that actually reaches the IC \( (P_{\text{on-chip}}) \) depends on the \( S_{11} \) as follows:

\[
P_{\text{on-chip}} = P_{\text{VNA}} \left( 1 - |S_{11}|^2 \right)
\]

When \( P_{\text{on-chip}} = p_c \) the IC activates and an abrupt change in the measured \( S_{11} \) is observed [31]. Consequently, the voltage level of the DC output port starts arising, and the \( p_c \) can be extracted from the measured \( S_{11} \) and \( P_{\text{VNA}} \).

A. Measurement Results

To our knowledge, only two commercially available ICs, the EM4152 [22] and the EM4325 [23], provide the required feature of a controllable DC output port. This paper relies on the characterization of the EM4325 IC \( (Z_{\text{chip}} = 7.6 - j 114 \, \Omega, p_c = -31 \, \text{dBm}) \), which operates in Battery Assisted Passive (BAP) mode, which means that the supply of the external component is provided by the battery \( (V_{\text{out}} = 3.3 \, \text{V}) \). A VNA [34] operating in the frequency band \( f_s = 0.4 - 5 \, \text{GHz} \) and with a power level \( P_{\text{VNA}} \) ranging from -20 dBm to 10 dBm was used. The results are visible in Fig. 4 and Fig. 5. Being the EM4325 operating in BAP mode, the sensitivity was approximately \( p_c = -31 \, \text{dBm} \) up to around \( f_s = 1 \, \text{GHz} \) (Fig. 4), coherently with the datasheet. Then, a sharp and monotonic increasing trend was measured, meaning that the IC performs worse when operating far from the UHF band, and the benefits of the battery strongly degrade, at least for
Fig. 4. Measured power sensitivity of EM4325 over frequency.

Fig. 5. Output DC voltage delivered by the EM4325 IC versus power-on-chip at different frequencies. Dashed lines indicate the threshold voltages for MEMS, PIN diodes, and varactor diodes.

the power-up. It is worth noticing that, up to 2.45 GHz, $p_c$ aligns with standard ICs operating in the UHF band.

The DC output voltage $V_{out}$ versus the power-on-chip $P_{on-chip}$ is visible in Fig. 5 for the set of frequencies listed in Table II. Since the external battery provides the output voltage, the EM4325 only needs to be turned on to achieve the maximum DC output $V_{out}^{max}$ (Fig. 5), which depends only on the battery capabilities (up to 3.3 V [23]). Moreover, once $V_{out}^{max}$ is reached, the output is stable and free of oscillations, damping, or drift.

B. Discussions

The measured operative sensitivities can be exploited to theoretically derive the maximum operating distances for a hypothetical reconfigurable EM-O integrating the previously mentioned IC. By considering ambient RF sources (whose Emission Power Levels (EPLs) are imposed by the Federal Communication Committee (FCC) and the European Telecommunications Standards Institute (ETSI)) under the hypothesis of polarization matching between the RF emitter and the reconfigurable EM-O and a realized gain of 0 dBi for both the receiver and the transceiver, the maximum activation distance can be calculated as [35]:

$$d_{max} = \frac{c}{4\pi} \sqrt{\frac{EPL}{p_o}},$$

where $c$ is the speed of light, and $f_o$ and EPL are the frequency and the maximum emission power level of the considered RF source, respectively. The resulting maximum allowed distances are listed in Table II and highlight that the IC can operate up to 1 m with 2.45 GHz Wi-Fi or Bluetooth signals. In contrast, the activation distance reduces to only a few centimeters at 5 GHz. This result suggests that, for higher frequencies, a dedicated RF source would be needed.

Regarding the type of tunable elements, it is possible to state that varactors, MEMS switches, and PIN diodes would be suitable for RAP ICs, since the maximum value of $V_{out}$ is stable, reached instantaneously, and compatible with the switching thresholds of the above-mentioned tunable components (as outlined by the features listed in Table III).

IV. PRELIMINARY FEASIBILITY EXAMPLES

In this section, we provide two feasibility examples to demonstrate the reprogramming capability of the proposed architecture in terms of the selective activation of antenna nodes and the beam shaping of a 3-element array. For the sake of simplicity, all three operating steps of Section II (programming, power-up, and operation) were carried out at 900 MHz.

A. Selective Activation of Nodes

A first example considered the EM4325 to realize a two-node system, in which a programming node controls the communication capability of an operating node. For the sake of simplicity, here $f_p = f_s = f_o = 900 MHz$. The programming node can be seen as a wireless security token (i.e., a device that is used in addition to, or in place of a password to gain access to another device [36]) for the operating node, which can be, for example, an RFID sensor.

TABLE III
RF TUNABLE ELEMENTS

<table>
<thead>
<tr>
<th>Type</th>
<th>Threshold [V]-[A]</th>
<th>Note</th>
</tr>
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<tbody>
<tr>
<td>PIN diode</td>
<td>0.6-0.8 V/0.1-1 mA</td>
<td>High Power</td>
</tr>
<tr>
<td>MEMS Switch</td>
<td>2.5-3.3 V/1-10 μA</td>
<td>Low power</td>
</tr>
<tr>
<td>Varactor diode</td>
<td>0.2V/1-10 nA</td>
<td>Voltage stability required</td>
</tr>
</tbody>
</table>
Fig. 6. (a) Schematic representation of layout for selective activation of RFID nodes. (b) When activated, the master IC sets the diode impedance to $Z_{\text{ON}}$, enabling the slave IC to respond to an RFID interrogation. (c) When the master IC is in the off state, the diode impedance is changed to $Z_{\text{OFF}}$, causing the slave IC to stop responding.

The programming node is equipped with the EM4325 IC (master IC), while the operating node integrates a Magnus S3 IC (slave IC) ($Z_{\text{chip}} = 7.6 - j114 \, \Omega$, $P_{\text{in}} = -16 \, dBm$ [37]) and a PIN diode (Fig. 6). The aim is that the slave IC can be enabled or not, depending on the state of the master IC. Indeed, when the master IC is powered up and its DC output port is activated, the diode impedance is set to $Z_{\text{ON}}$, allowing the slave IC to respond to an RFID interrogation. On the other hand, when the DC output port is deactivated, the diode impedance is set to $Z_{\text{OFF}}$, even if the master IC is powered up, causing the slave IC to stop responding.

The programming and operating nodes were realized as two dipoles, orthogonally arranged for coupling minimization purposes (Fig. 7). The ICs were matched to their respective antenna impedance through a T-match [35] and the PIN diode [38] was connected to the DC output pin of the master IC and the T-match of the slave IC so that, by changing the state of the master IC, a substantial variation of the current flowing on the T-match can be imposed. More specifically, when the diode is off, its impedance resembles an open circuit, leading to a complete mismatch of the operating tag and its inactivation. In contrast, when the diode is on, the operating tag results matched and capable of replying to the RFID interrogation.

Finally, ferrite beads [39] were also integrated with the layout for both dipoles to decouple them from the 3.3 V DC voltage of the battery.

Preliminary simulations of the system were performed using CST Microwave Studio 2023. The dipoles were printed on a 1.6 cm thick FR-4 substrate ($\epsilon_r = 4.3$, $\tan\delta = 0.025$), and the PIN diode was simulated through its .s2p file. Geometrical parameters (Fig. 7) were optimized to achieve the behavior described in Fig. 6. Indeed, when the PIN diode is on, the impedance matching is achieved (power transmission coefficient [35] $\tau_1 = 0.98$, $\tau_2 = 0.9$), while when it is switched to its off state, the slave IC is mismatched ($\tau_2 = 0.08$), as illustrated in Fig. 8.

Measurements were performed with a prototype that was realized by etching copper from an FR-4 Printed Circuit Board (PCB) using a milling machine, while electronic components (IC, diodes, and ferrite beads) were soldered with the help of a bench soldering iron. The experimental setup (Fig. 9) consisted of a circularly polarized antenna (patch with broadside gain $G_R = 7.5 \, dBic$) placed 30 cm away from the prototype and connected to the TagFormance UHF Pro station for interrogation. Realized gains were retrieved by the turn-on power method [28]. Fig. 10 compares the measured and simulated data for both antennas in both states, highlighting the good
agreement and the effective enabled/disabled communication with the slave IC in the different states.

B. Beam Shaping

The second experiment aims to demonstrate the beam’s shaping of a 3-elements antenna array. The array comprises the programming node and two operating nodes (Fig. 11). The programming node includes EM4325 while operating nodes integrate only a PIN diode. When the IC is activated, the PIN diodes are the impedance leading to a variation in the currents flowing through their respective antennas (from $I_{1\text{ON}}$ to $I_{1\text{OFF}}$, $I_{2\text{ON}}$ to $I_{2\text{OFF}}$, and vice versa) and thus in the radiation pattern of the whole array (Fig. 11).

The system was designed as depicted in Fig. 12. Again, the IC impedance was matched through a T-match, and dipoles were placed on an FR-4 substrate. PIN diodes were connected to the DC output pin of the IC and the negative pin of the battery (which was placed on the back side) via ferrite beads. Geometric parameters, i.e., the lengths of the programming and operating nodes and their mutual distances, were chosen as the result of a parametric analysis oriented to optimize the realized gain $G_\tau$ of the array. The system was designed to work as follows: when the RFID IC is in the on state (Yagi mode) and activated, both diodes are on; hence, they ideally act as short circuits, and the typical Yagi-Uda radiation pattern is achieved. 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” pattern. As expected, the RFID programming effectively changes the pattern of the currents of the structure, as visible in Fig. 13. Indeed, in the dipole mode operation, only weak currents flow through the passive elements, while in the Yagi mode, currents are sensibly higher.

The numerical analysis was validated by measuring the realized gain and the radiation pattern using the TagFormance UHF Pro station. The prototype is visible in Fig. 14. Fig. 15 compares the array antenna’s simulated and measured realized gain for both states in the end-fire direction. Measurements agree with simulations, and both highlight a notable change.
in the gain absolute values due to the transition from the Yagi mode to the Dipole mode. Differences between simulations and measurements could be caused by uncertainties in the simulated equivalent impedance of the PIN diodes, which are highly voltage-sensitive. Finally, the measured radiation patterns are shown in Fig. 16. Also in this case, there is a good agreement with simulations, definitely proving the radiation pattern reconfiguration capabilities of the proposed system. Indeed, in the Yagi-mode, the array has an endfire radiation pattern with a maximum realized gain of 4 dB ($G^\text{sim, max}_{\text{Yagi}} = 6.6$ dB) for $\phi = 0^\circ$ and a front-to-back ratio of about 12 dB. In the dipole mode, instead, the antenna exhibits an isotropic radiation pattern with a realized gain of -4.7 dB ($G^\text{sim, max}_{\text{Dipole}} = -2.2$ dB).

V. CONCLUSIONS

This paper introduces, discusses, and experimentally validates the idea of RFID-based wireless programmable electromagnetic objects. When compared with traditional electronic tuning mechanism in which an FPGA and several shift registers provide the bias voltage required by the tunable components [12], the proposed RFID-Based wireless programmability provides similar output voltages and currents (Table IV) and several advantages which are listed in Table IV and discussed below:

- **Reduced Power Consumption**: The power required to drive a reconfigurable electromagnetic device is composed of the dynamic power consumed by the tunable elements ($P_{\text{dynamic}} = N \cdot P_{\text{switch}}$), where $N$ is the number of RF switches) and the static power ($P_{\text{static}}$) consumed by the control circuit. Typically, the power required by an FPGA is $\approx 5$ W [40], [17], while the RFID IC used in this paper consumes only 5 – 30 $\mu$W from the battery [23].

- **Reduced Cost**: The cost of an FPGA is around hundreds of euros, while that of an RFID IC is less than 1 euro. However, it should be noted that a single FPGA is capable of independently driving hundreds of tunable components, while an RFID IC can only set one state at a time, which means that the minimum number of required ICs is equal to the number of desired reconfigurability bits. Therefore, the proposed approach is beneficial for all those reconfigurable devices that require a limited number of bits, as the cost is significantly reduced, while for more complex structures, the traditional reconfiguration mechanism should still be preferred.

- **Reduced Complexity**: In addition to removing physical wires, the proposed solution could also simplify the structure by eliminating the complicated biasing lines needed to drive the tunable elements. Indeed, since RFID ICs are miniaturized and lightweight components, they can be distributed across the reconfigurable EM-O, reducing the length and number of required biasing lines and thus limiting unwanted interference, losses, and radiation pattern distortion. Moreover, the device can also be made flexible and deployable in all those environments where cables are not allowed.

However, the RFID-Based wireless reconfiguration mechanism also presents some limitations and challenges that need to be addressed, especially considering reconfigurable EM-O operating at higher frequencies. For instance, the IC characterization has highlighted that the IC sensitivity $p_c$, and thus the activation distance $d_{\text{max}}$, degrade as the frequency $f_s$
increases, pointing out that it could be necessary to include a dedicated RF source in the system architecture, thereby reducing the benefits of reduced complexity discussed above.

Future activities will be devoted to characterizing the feasibility of adopting a pure passive configuration for battery removal and validating activation and operation through different ambient sources.

REFERENCES


Francesco Lestini (Student Member, IEEE) was born in Genzano di Roma, Italy, in 1997. He received the B.S. and M.S. degrees (Hons.) in medical engineering in 2019 and 2021, respectively, from the University of Rome Tor Vergata, Rome, Italy, where he is currently pursuing the Ph.D. degree in computer science, control and geoinformation with the Pervasive Electromagnetics Lab. Since 2023, he has been a part-time R&D RF Engineer with RADO6ENSE Srl. His research focuses on the wireless reconfigurability of electromagnetic devices through RFID technology and on developing epidermal RFID grids for distributed skin temperature measurement. Mr. Lestini is also part of the Cyber4Health observatory, which focuses on raising international awareness about the need for pre-market regulations related to medical devices’ Cyber and Physical security. He received the Best Paper Award at the 7th edition of SpliTech Conference (2022) on Smart and Sustainable Technologies and an Honorary Mention by URSI for the Young Scientist “Roberto Sorrentino” Award (2023).

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