Reader Antennas Requirements in Chipless RFID Systems with Linear and Circular Polarization

Filippo Costa
Dept. of Information Engineering,
University of Pisa
Pisa, Italy
filippo.costa@unipi.it

Simone Genovesi
Dept. of Information Engineering,
University of Pisa
Pisa, Italy
simone.genovesi@unipi.it

Giualiano Manara
Dept. of Information Engineering,
University of Pisa
Pisa, Italy
giuliano.manara@unipi.it

***Abstract*—Two efficient reading approaches for chipless RFID are compared. The first approach uses a linear polarization interrogation with depolarizing tags able to reflect an electromagnetic signal with orthogonal polarization state with respect to the impinging one. In the second approach a circular polarization interrogation is sent to the tag which scatters it back with opposite rotation sense. The two methods are described in terms of both conversion efficiency and performance at a system level. It is underlined that one of the main requirements for obtaining good performance of the chipless RFID system relies on the design of the reader transmitting and receiving antennas which should be wideband and guarantee a low level of radiated cross-polarization, together with a low-mutual coupling.**

Keywords— Antennas, Chipless RFID, Circular Polarization, Depolarizing tags, Polarimetric scattering.

I. INTRODUCTION

Classical Radio Frequency Identification (RFID) tags comprise an antenna and an integrated circuit (IC) that performs the data processing and is powered by extracting energy from the interrogation signal transmitted by the RFID reader.

On the other hand, Chipless RFID technology is based on a modulation performed on the backscattered signal without any active component on the tag. The technology relies only on the shaping, in frequency or in time, of the response provided by an RF passive label. The challenge in designing chipless RFID tags is how to perform data encoding without the presence of a chip.

The signal backscattered by the tag contains the information in terms of amplitude modulation, phase modulation etc. In particular, amplitude modulation [1], phase quantization [2], [3], frequency shifts [4], [5], time delays and hybrid approaches mixing some of the aforementioned quantities [6]–[8] have been demonstrated.

In order to improve the detectability of the tag and also improving the immunity to multipath several detection approaches have been investigated. In particular, dual polarization interrogation [9], cross-polarization exploitation [10], [11] or signal processing techniques have been investigated [12]. The solutions based on co-polar interrogation usually struggle if the chipless RFID tag is placed on a metallic object since the scattering of the tag can be overwhelmed by the strong electromagnetic echo of the hosting platform. Techniques based on depolarizing tags [10] [11] are more efficient in isolating the tag contribution but they usually require a particular relative orientation between the tag and the transmitter/reader antennas in order to maximize the probability of correct detection. In [13], [14] circularly-polarized chipless tags are investigated.

This paper is devoted to compare the performance of two efficient encoding/detection schemes, *i.e.* the depolarizing tags both with linear and circular polarization interrogation. Both approaches exhibit a good immunity to multipath and good performance when the tag is located on metallic platforms. However, the circularly polarized interrogation features the insensitivity with respect to the reader antenna orientation, differently from linear interrogation. The latter property is very appealing from a practical point of view. However, a further rigorous investigation of the system performance in comparison with the linear depolarizing one is needed.

II. CHIPLESS RFID SYSTEM BASED ON DEPOLARIZING LINEARLY POLARIZED INCIDENT E-FIELD

Let us consider a linearly polarized wave impinging on a chipless tag laying on the *xy* plane as shown in Fig. 1. The impinging field $\underline{E}^{inc}$ can be expressed as:

$$\underline{E}^{inc} = E_x \, \underline{i}_x + E_y \, \underline{i}_y , \tag{1}$$

where $\underline{i}_x$ and $\underline{i}_y$ are the unit vectors along x-axis and y-axis, respectively, and $E_x=E_0 cos(\phi_{in})$, $E_y=E_0 sin(\phi_{in})$ represents the magnitude of each component of the impinging field E_0 directed along $\phi_{in.}$ The reflected electric field $\underline{E}^{refl}$ can be expressed as:

$$\underline{E}^{refl} = \overline{\overline{\Gamma}} \underline{E}^{inc} = \begin{bmatrix} \Gamma_{xx} & \Gamma_{xy} \\ \Gamma_{yx} & \Gamma_{yy} \end{bmatrix} \left(E_0 \, \underline{i}_x + E_0 \, \underline{i}_y \right), \tag{2}$$

where Γ_{xx} and Γ_{yy} are the copolar reflection coefficients whereas Γ_{xy} and Γ_{yx} are the cross-polar ones in the cartesian coordinate system *xy*. If the impinging electric field is along $\phi_{in}=45°$ the components of the impinging field are identical. In this case, if the tag is able to reverse just one of the two components of the impinging field at the resonance (*e.g.* $\Gamma_{xx} = \Gamma_{yy} = -1$ with $\Gamma_{xy} = \Gamma_{xy} = 0$), then the reflected field will be polarized along the cross-polar direction. In general, in order to compute the backscattered response of the tag along the cross-polar component, it is more convenient rotating the system of coordinates along the direction of the impinging electric field, say *uv* cartesian coordinate system aligned with the incident electric field ($\underline{E}^{inc} = E_0 \underline{i}_u$). Doing that, the co-polar and cross-polar components of the reflected field can be written as:

$$E_u = \Gamma_{uu} E_0 , \; E_u = \Gamma_{vu} E_0 , \tag{3}$$

III. CHIPLESS RFID SYSTEM BASED ON DEPOLARIZING CIRCULARLY POLARIZED INCIDENT E-FIELD

Let us consider a right-handed circularly polarized (RHCP) plane wave generated by a RHCP antenna propagating in air along positive z direction. The wave impinges on a planar interface. The incident field $\underline{E}^{inc}$ can be written as [14]:

$$\underline{E}^{inc} = E_0\, \underline{i}_x + jE_0\, \underline{i}_y\,, \tag{4}$$

where $\underline{i}_x$ and $\underline{i}_y$ are the unit vectors along x-axis and y-axis, respectively, and E_0 represents the magnitude of each component. The reflected electric field $\underline{E}^{ref}$ can be expressed as:

$$\underline{E}^{refl} = \underline{\underline{\Gamma}}\,\underline{E}^{inc} = \begin{bmatrix} \Gamma_{xx} & \Gamma_{xy} \\ \Gamma_{yx} & \Gamma_{yy} \end{bmatrix} \left(E_0\, \underline{i}_x + jE_0\, \underline{i}_y\right), \tag{5}$$

where Γ_{xx} and Γ_{yy} are the co-polar reflection coefficients whereas Γ_{xy} and Γ_{yx} are the cross-polar ones. By employing a chipless tag able to reverse just one of the two components of the impinging field at the resonance (e.g. $\Gamma_{xx} = \Gamma_{yy} = -1$ with $\Gamma_{xy} = \Gamma_{xy} = 0$), the circularly polarized reflected field will have an opposite rotation handiness but the same polarization of the impinging field since the direction of propagation is reversed. On the contrary the field scattered by a PEC surface with $\Gamma_{xx} = \Gamma_{yy} = -1$ and $\Gamma_{xy} = \Gamma_{xy} = 0$ will have an opposite polarization (LHCP). The performance of the tag with impinging circularly polarized wave can be addressed by computing the Polarization Loss Factor (*PLF*), which summarizes the amount of power lost by polarization mismatch at the receiver side. Indeed, in order to maximize the power received at the reader side a proper antenna should be selected. The PLF is defined as follow:

$$PLF = \left|\underline{\rho}_{ref} \cdot \underline{\rho}_{RX}\right|^2\,, \tag{6}$$

where $\underline{\rho}_{\mathrm{ref}}$ is the polarization vector of the reflected wave and $\underline{\rho}_{RX}$ is the polarization vector of the CP receiving antenna:

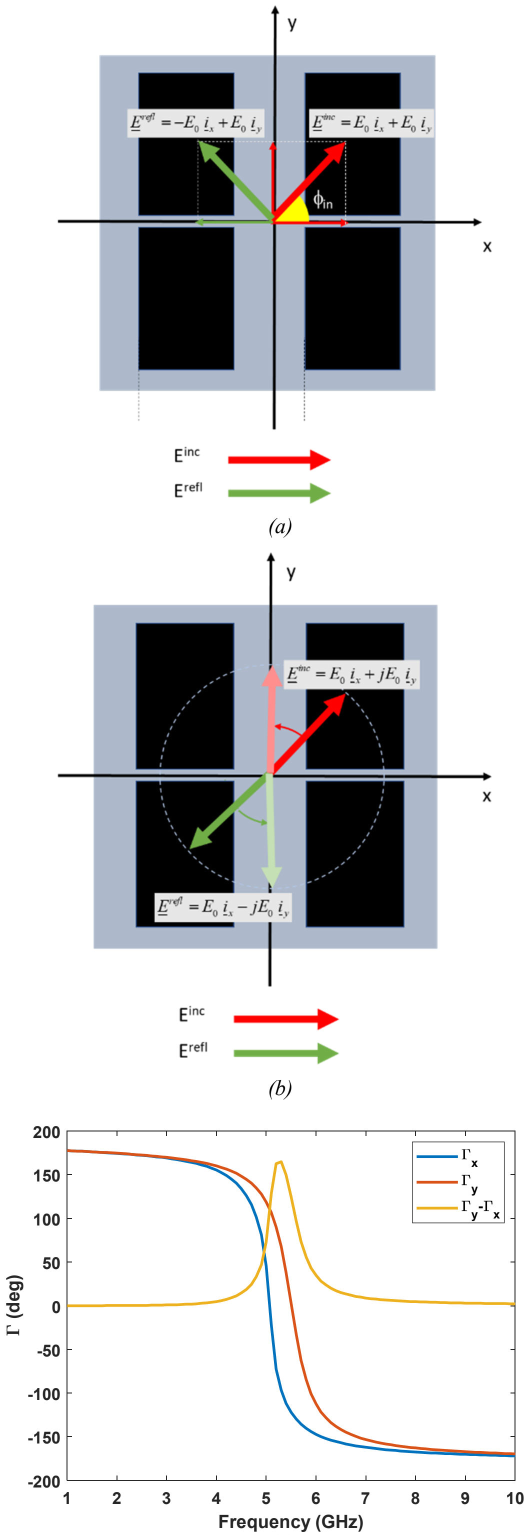
$$\underline{\rho}_{refl} = \frac{\underline{E}_x^{refl}\,\underline{i}_x + \underline{E}_y^{refl}\,\underline{i}_y}{\left|\underline{E}^{refl}\right|}, \quad \underline{\rho}_{RX}^{RH/LH} = \frac{1}{\sqrt{2}}\left(\underline{i}_x \pm j\underline{i}_y\right) \tag{7}$$

The PLF is defined so that it attains a value of 1 if there is no polarization mismatch, *i.e.*, the antenna receives the maximum possible power for the given incident power density of the wave. A PLF equal to 0 indicates complete polarization mismatch and inability to capture power from the incident wave.

In case of the clipless tag with polarization reverting properties at the resonance (that is the tag reflects the same polarization state sent by the reader) the PLF is maximized by employing an RH antenna in reception. The same antenna is also able to filter out the fields reflected outside the resonance frequency of the tag (where no perfect polarization conversion is achieved) and those reflected by metallic surfaces. The necessary condition is the same needed for a linear reflection polarization converter [15], [16].

IV. CASE STUDY

As an example, chipless tag comprising an array of rectangular patches on top a grounded dielectric substrate characterized by a thickness of 1 mm and a dielectric permittivity equal to 4.4 is considered. The periodic array on topo of the dielectric is characterized by a periodicity of 20 mm. The size of the patches are 19 mm along x-direction and 18.5 mm along y-direction. The tag is analyzed with an equivalent transmission line formulation [1]. In Fig.1c, the phase of the reflection coefficient along x and y direction is reported. As it is evident, the phases are slightly shifted in frequency and therefore the phase difference becomes equal to 180°, the required condition both for linear and CP chipless system, at a single frequency. By playing with the phase responses, the peak can be rendered more or less sharp.



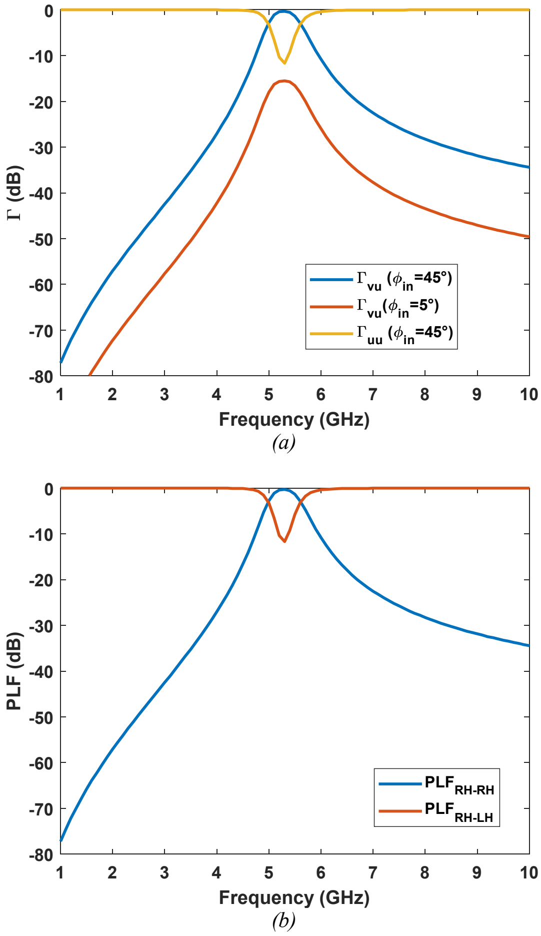
(a)

(b)

(c)

Fig. 1. (a) Sketch of a depolarizing linearly polarized chipless system. (b) Sketch of a depolarizing circularly polarized chipless system. (c) Phase reflection coefficient of the x and y component of the reflection coefficient of a chipless tag formed by a periodic array of rectangular patches located on a grounded substrate with a thickness of 1 mm and a dielectric permittivity of 4.4. The periodicity of the patch alignment is D=20 mm in both planar directions and the gap between the patches is w_x=1 mm and w_y=1.5 mm along x and y direction, respectively.

In order to quantify the conversion efficiency of the depolarizing system and the circularly polarized system, the reflection coefficient Γ_{vu} and the PLF are evaluated as a function of frequency in Fig. 2.



(a)

(b)

Fig. 2. (a) Reflection coefficient for cross-polar and co-polar components in linear polarized clipless system (b) PLF for co-polar and cross polar CP chipless system.

In the case of linear polarized system, the tag performs an optimal polarization conversion when the phase difference becomes 180° but the imping field must be directed towards ϕ_{in} =45° in order to have equal x and y components of the imping electric field. As the impinging angle is varied, the polarization conversion of the tag deteriorates leading to rapid worsening of the system performance. On the contrary, in the case of CP interrogation, the electric field is continuously rotating on the xy plane and therefore the polarization conversion is performed in an optimal way independently of the rotation of the reader antenna. This is a strong benefit in a practical operating scenario. However, the use of the CP interrogation poses additional constraints on the reader side where two wideband CP antennas should be designed instead of linearly polarized ones.

V. LINK BUDGET

The possibility of detecting the tag in a chipless RFID system depends on the amount of the received power associated with the signal containing information and the power not associated with the same signal, classified as disturb or noise. The useful power scattered by the tag can be computed, in a first approximation, by using the Friis equation:

$$P_R = \frac{G_T G_R P_T \lambda^2}{(4\pi)^3 r^4}\sigma \quad , \tag{8}$$

where σ represents the Radar Cross Section (RCS) of the tag. In case of metallic plate of sides L and w, the RCS, σ, can be evaluated by using the physical optic relation:

$$\sigma_{plate} = \frac{4\pi L^2 w^2}{\lambda^2} \quad , \tag{9}$$

When the metallic surface is replaced by the polarization selective surface which allows to introduce the proper phase gap between the x and the y components of the reflected field at the resonance frequency, the RCS is modulated in amplitude. The received power reaches its maximum only at the resonance frequency of the tag where the RCS of the tag becomes equal to the RCS of the metallic plate.

The detection of the tag can be performed correctly only if the power associated with the information signal at the receiver is higher with respect to the undesired contributions from the background collected by the reader. Even in an ideal environment, several undesired contributions are collected by the receiving system. Three main undesired contributions can be easily isolated in a realistic system: the thermal noise at the receiver, undesired signals collected by the receiver antenna due to its non-ideality (mutual coupling due to cross-polar component) and the scattering from the hosting platform (especially if it is metallic). In summary, the total undesired signal is the sum of the power of the three aforementioned contributions:

$$\mathrm{P}_{\mathrm{r}}^{disturb} = \mathrm{P}_{\mathrm{r}}^{noise} + \mathrm{P}_{\mathrm{r}}^{pol-mismatch} + \mathrm{P}_{\mathrm{r}}^{coupling} . \tag{10}$$

The performance of the reader antennas play a crucial role in determining the performance of the two different encoding systems since they will directly impact on the level of mutual coupling term and on the polarization mismatch term. For this reason, the reader antenna design represents one of the most important requirements in the analyzed chipless schemes. In particular, the antennas should be wideband, and also characterized by a low-mutual coupling and a low cross-polar component. In order to obtain a high detection probability is therefore necessary to maximize the signal to noise ratio (SNR) at the receiver. The latter can be expressed as:

$$SNR = \frac{P_R^{signal}}{\mathrm{P}_{\mathrm{r}}^{disturb}} \quad . \tag{11}$$

A thorough analysis of all these terms contributing to the system SNR will be provided in order to show a clear assessment of the performance of the two different encoding paradigms.

VI. CONCLUSION

A system level study of a chipless RFID system with two different encoding schemes is addressed. The depolarizing scheme and the circular polarization scheme will be analysed in terms of polarization conversion efficiency and system level efficiency. Both the encoding approaches will be tested to show good immunity to multipath, robustness with respect to undesired reflections of metallic surfaces because of polarization mismatch.

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