Impact of the Polarization over the Read Range in Chipless RFID

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***Abstract*—This paper presents a fair comparison between the read range of chipless RFID in co-polarization and cross-polarization in real environments. This comparison is a direct consequence of the bound on the read range for the chipless technology presented in [1]. The approach is based on an analytical model and validated by simulations and measurements. Results are mainly function of the considered residual environment. In static environments (such as anechoic chambers), co-polarization offers the highest read range due to the higher Radar Cross-Section (RCS) of the resonators with identical residual environments. However in dynamic environments (which include all real environments), cross-polarization is more robust since, even if resonators RCS is 6 dB lower than co-polarized tags, the associated residual environment is 10 dB lower. Thus read range in cross-polarization outperforms by a factor of 26% the one obtained in co-polarization in almost all real applications.**

***Index Terms*—Chipless RFID, linear time-invariant system, radar cross-section, read range, RFID, polarization.**

I. Introduction

CHIPLESS technology offers a promising solution to reduce the cost of classical UHF identification. Reading is classically done by sending a Ultra-Wildband (UWB) signal towards the chipless tag and by receiving the backscattered signal. Tag ID can then be extracted by the reader form the received signal using different approaches.

Polarization used by chipless reader is mainly of 2 types: co-polarization, in which both emitting and receiving antennas use the same linear polarization, and cross-polarization, where emitting and receiving antennas use orthogonal linear polarizations. A lot of literature has already been published on this topic over the past decade which can not be covered here.

Also, since associated read range in real environments depends on several parameters, current research works did not select a clear direction yet. Thus, both co-polarization and cross-polarization configurations are still considered at that time. Independently, in [1], an analytical bound on the chipless read range has been obtained and shows that chipless read range will remain significantly lower than the one obtained in classical UHF RFID due to the linearity of the chipless tag. Results proposed in this article are directly based on the analytical model and the bound presented in [1] and allows to clearly compare the performance in term of read range for co-polarization and cross-polarization reading methods in real environments.

II. Chipless Read Range

By remarking that a chipless tag is a linear time-invariant system as any other object present inside the environment, any power transmitted by the reader will be backscattered by the tag but also reflected by the environment over the exact same bandwidth. Note that these two contributions can not be separated perfectly and significantly decrease the read range compared to the one obtained in perfectly isolated free-space. More importantly, since both tag and residual environment are LTI systems, increasing the transmitted power does not have any effect over the read range. Complete demonstration is presented in [1] where read range can finally be expressed as:

$$d_c \leq \sqrt[4]{\frac{G_t G_r \lambda^2 \sigma(f)}{(4\pi)^3 |\epsilon(f)|^2}} \tag{1}$$

where $\sigma(f)$ is the RCS of the chipless tag and $|\epsilon(f)|^2$ is the residual environment, which is the key concept to determine the performance of any chipless reading system. Read range determined by (1) does not depends on the transmitted power used by the chipless reader and is significantly lower compared to the one extracted from the radar equation (which is classically used to determine the read in the literature, see for example [2]–[7]). Moreover, (1) allows to clearly separate the contribution of the tag *i.e.*, $\sigma(f)$ and the contribution of the residual environment *i.e.*, $|\epsilon(f)|^2$ on the read range of the chipless tag. This observation allows to realize a fair comparison between co and cross-polarization reading methods based on the independent study of the RCS and the residual environment.

III. Results

A. Radar Cross-Section

The following study considers three different tag designs: rectangular loop, C-shape and dipoles at $45°$ with ground plane [8] and are presented in Fig. 1. All considered tags have been designed on 0.8 mm Rogers 4003C substrate. C-shape and loop resonators are classically read in co-polarization whereas dipoles at $45°$ with ground plane have been designed to be read in cross-polarization.

For all chipless tags, RCS can be defined as:

$$\sigma(f) = \lim_{r \to \infty} 4\pi r^2 \frac{|E_s|^2}{|E_i|^2} \tag{2}$$

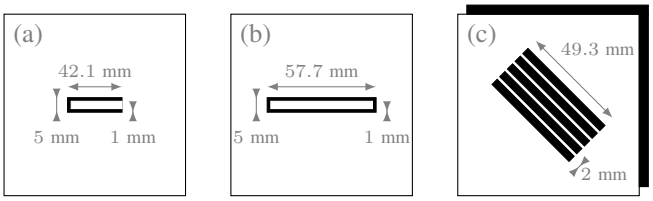

Fig. 1. Resonators used in the study: (a) C-shape resonator, (b) rectangular loop and (c) dipoles with ground plane. All resonators use a 0.8 mm Rogers RO4003C substrate.

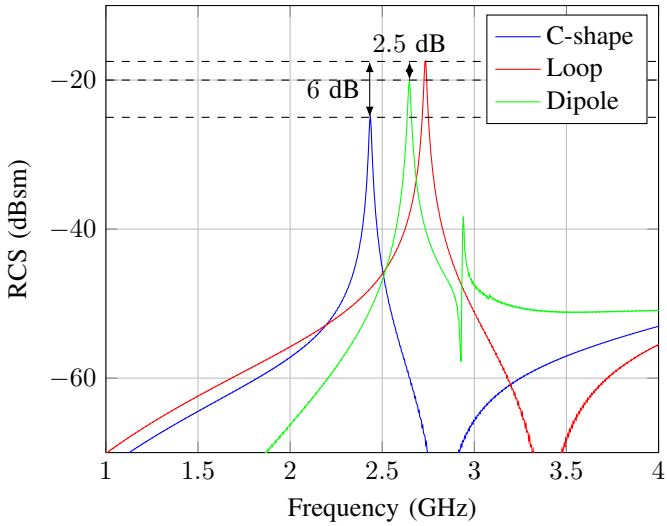

Fig. 2. Radar cross-section of classical chipless resonators for different length l (a) C-shape in co-polarization, (b) rectangular loop in co-polarization and (c) 45° dipoles in cross-polarization [8].

where E_i and E_s are respectively the incident and backscattered electric field and can be easily simulated using EM solvers. Exact RCS value at the resonance depends on the resonator geometry. Fig. 2 presents the RCS for the considered tags. All the resonators have been designed to resonate between 2 and 3 GHz. The highest RCS of -17.5 dBsm is achieved for the loop resonator whereas dipole and C-shape resonators are characterized by a RCS at the resonance respectively 2.5 and 6 dB lower than the loop resonator. Finally note that RCS of a resonant structure at 45° is 6 dB lower than the "correct" orientation in co-polarization since the induced current has components in both polarizations and generates the same RCS in co-polarization.

B. Residual Environment

Residual environment is the key parameter to characterize the read range of any chipless systems. This quantity has been defined in [1] and can be estimated by measuring two times the (dynamic) environment. If the chipless reading system is based on a Vector Network Analyzer (VNA), $|\epsilon(f)|^2$ can simply be expressed as:

$$|\epsilon(f)|^2 = |S_{YXe_1} - S_{YXe_2}|^2 \quad (3)$$

where S_{YXe_n} are two independent measurements of the S-parameter without the tag. Note that S_{YXe_1} is never equal

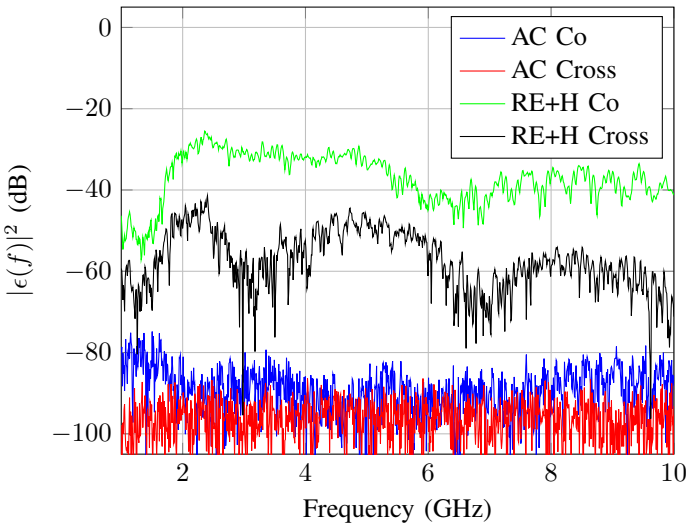

Fig. 3. Different measured residual environments obtained in anechoic chamber (AC) and real environment with the hand in front of the antenna (RE+H) in co-polarization and cross-polarization.

TABLE I
AVERAGE RESIDUAL ENVIRONMENT $|\epsilon(f)|^2$ OF DIFFERENT OBJECTS MEASURED AT A DISTANCE OF 20 CM WITH A VNA BASED READER

Objects	Co-polarization	Cross-polarization
Empty AC (static)	-82 dB	-81 dB
Operator at 1 m	-55 dB	-57 dB
Paperclip	-46 dB	-55 dB
1$ coin	-40 dB	-62 dB
Hand	-37 dB	-48 dB
Empty packaging	-48 dB	-56 dB

S_{YXe_2} in dynamic environments (which include all real environments). Also, note that (3) underestimates the residual environment since coupling between the tag and the environment is not taken into account.

Fig. 3 presents the measured residual environment obtained from a VNA-based reader and compares the performance of co-polarization (*i.e.*, S_{11}) and cross-polarization (*i.e.*, S_{21}) reading methods for an IF bandwidth of 1 kHz for both configurations. We can see that associated residual environment in anechoic chamber are relatively close and below -80 dB. Note that this result corresponds to the lowest residual environment which can be measured by the instrument. In more classical environments (*i.e.* when the operator is close to the instrument), this value is usually around -55 dB for both polarizations. However, when the hand is placed in front the antenna at a distance of 20 cm, we can see that cross-polarization presents a lower residual environment compared to co-polarization. Over the full bandwidth, average residual environment is equal to -37 dB and -48 dB for co-polarization and cross-polarization respectively. Thus, cross-polarization present an higher robustness compared to co-polarization.

Finally, Table I presents the average residual environment of different objects measured at a distance of 20 cm by a VNA between 3 and 8 GHz. In each case, the same procedure

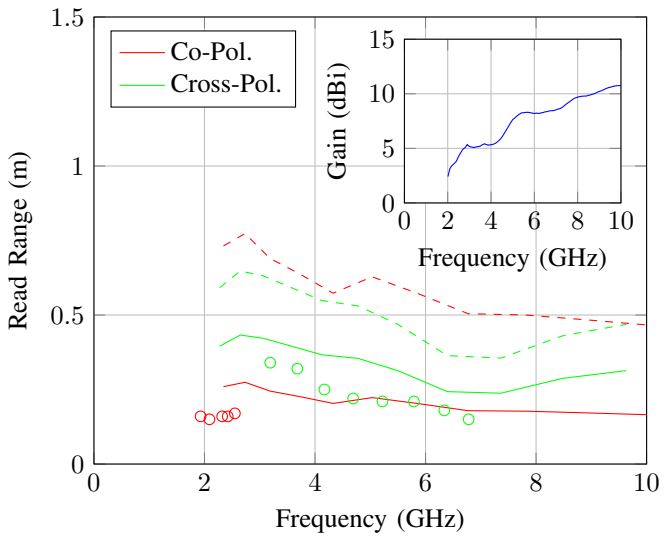

Fig. 4. Read range in co-polarization and cross-polarization obtained from (1) in (static) real environments ($|\epsilon(f)|^2 = -55$ dB), (dynamic) real environment by holding the tag with the hand ($|\epsilon(f)|^2 = \{-37; -48\}$ dB). Marks correspond to the measured read range in real environment by holding the tag with the hand. Inset: Satimo QH2000 gain as a function of the frequency.

was applied, two measurements are done, one in empty environment and a second one with the considered object. In anechoic environment, the average residual environment could be as low as -80 dB however, when objects are added or moved, residual environment can be drastically increased even by slight modification or variation of the environment. For example the simple presence of a paperclip adds a contribution of 36 dB in co-polarization and 26 dB in cross-polarization. These results directly affect the read range of the chipless system in the considered dynamic environment.

C. Read Range Evaluation

Read range achieved by a chipless tag in real environment can now be determined using (1) and the results obtained for the tag RCS $\sigma(f)$ and the residual environment $|\epsilon(f)|^2$.

In static environments, co-polarization achieve the highest read range since RCS is higher than the one obtained in cross-polarization and residual environment is identical in both cases around -55 dB. Results are presented in dashed line in Fig. 4 in co-polarization (for the loop resonator) and in cross-polarization (for the dipoles) with a residual environment of $|\epsilon(f)|^2 = -55$ dB in both configurations. However, an interesting point comes when dynamic environments are considered. In this case, RCS in cross-polarization is slightly reduced compare to co-polarisation (6 dB if a co-polarization resonator is rotated by $45°$), however, residual environment is significantly reduced (more than 10 dB if the resonator is hold by the user hand). Thus for the same reader parameters, cross-polarization offers a advantage of 4 dB compared to co-polarization independently of all others considerations. This factor represents an improvement of 26% for cross-polarization in term of read range compared to co-polarization in real environments. Fig. 4 presents the achievable read range obtained with (1) in real environment when the tag is hold by the user hand in co-polarization (for the loop resonator, $|\epsilon(f)|^2 = -37$ dB) and cross-polarization (for the dipole resonator, $|\epsilon(f)|^2 = -48$ dB). Exact gain values for the Satimo QH2000 antenna have been measured using a MVG Starlab and presented in the inset of Fig. 4. Measurements of the read range when tag is hold by the hand are also presented with dot markers for both polarizations. Note that measured read ranges have been obtained using a single empty measurement without the hand and without using post-processing technique. In each case, the measured read range is estimated by moving the tag away from the antenna until the peak amplitude can not be detected by the VNA. Also, the predicted read range is in good agreement with the measured ones for all frequencies and in both polarizations with a difference lower than 20 cm. Note that, difference can be explained by the structural mode of the tag itself and the coupling with other object in the tag's vicinity which also increase the residual environment.

IV. Conclusion

This paper presents a comparison of the read range of chipless system based on co-polarization and cross-polarization. Results rely on the analytical model presented in [1] and shows that maximum read range is obtained in co-polarization in (static) anechoic chamber. On the other side for (dynamic) real environments, cross-polarization resonators are usually affected by a RCS 6 dB lower than co-polarization ones, however the associated residual environment can be 10 dB lower than in co-polarization. Consequently, in (dynamic) real environments, cross-polarization offers the best performance in term of read range with an improvement of 26% compared to co-polarization which make this polarization a better candidate for real applications.

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