Square-shape fully printed chipless RFID tag and its applications in evacuation procedures

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***Abstract*- Herein, square-shaped chipless RFID tags are reported. Thereby, the development of the design, the applied fabrication process and the experimental verification are described. The designed tags, which are based on Frequency Selective Surfaces, are produced by screen printing on flexible PET and paper substrates and are considered suitable for the fabrication by means of roll-to-roll printing technologies. The functionality is proved by both, the measurements inside and outside the anechoic chamber. In order to corroborate the tag's independence to the position feature, the tags are further measured for several rotation and tilt angles. During measurements in the anechoic chamber, a reading distance up to 1.8 m could be demonstrated. Furthermore, a new optimized methodology for semi-automatic measurements that reduces the time per measured tag is introduced. Moreover, for the first time a chipless RFID tag to be applied in evacuation procedures under crisis events is proposed.**

***Index terms:* RFID, Printed electronics, IC, SMD, Frequency Selective Surfaces (FSS), Roll-to-Roll (R2R), polyethylene terephthalate (PET), fire resistant circuit board material (FR-4).**

I. Introduction

THE results, introduced in this paper, constitute a part of the achievements attained within eVACUATE project, an EU initiative, which aims at the development of an intelligent evacuation system for complex venues [1]. The objective of eVACUATE project is to provide a valuable tool to identify, designate and sustain an optimal evacuation route adapted dynamically according to current and evolving circumstances.

One of the main components of this tool is the named chipless RFID system. The chipless RFID system provides to the eVACUATE's framework the number and type of persons that have crossed through a particular position (gate) at the venue. This system is based on a very novel approach that combines the use of radar technology with radio frequency identification methodologies at a very low cost per tag. The chipless RFID system is composed by the chipless RFID reader and the chipless RFID tag. A block diagram for the whole system is shown in Fig. 1a.

The chipless RFID reader is, in fact, an adapted version of an Ultra-Wide-Band (UWB) frequency radar [2]. The main function of the reader is to send a pulse to excite the tag and to collect the backscattering signal from it. Additionally, the reader contemplates a digital processing unit responsible for the processing of received signal and the extraction of the information stored in the tag as well as the communication unit to connect the system to the eVACUATE's framework.

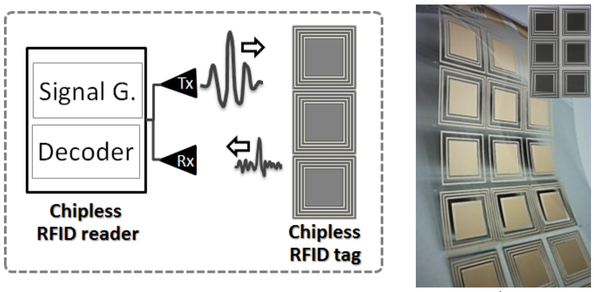

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Fig. 1. a) The chipless RFID system architecture. b) Actual aspect of a chipless RFID tag printed on PET material.

The chipless RFID tag is an inexpensive, passive and fully printed device responsible to store the information that identifies the type of person crossing through a gate. The information is stored in the tag by using the resonant features of the geometry of the tag [3, 4]. The tags, as shown in Fig. 1b, were produced by screen printing, utilizing a micro-particle based silver-ink.

This paper is devoted to the design, manufacturing and measuring of a 4 bit chipless RFID tag that fulfills the specific requirements of eVACUATE project. The tag design is inspired by Frequency Selective Surfaces (FSS) and presents a periodical-like structure to increase the performance behavior and thus obtain extended reading ranges - higher than obtained for a non-periodical-like tag. In particular, a reading distance up to 1.8 m is reported.

Additionally, this paper introduces an optimized methodology to read the information stored in the chipless RFID tag. This methodology is aligned to the development of a stand-alone reading device, part of the whole chipless RFID system.

II. Comparison with Similar Work

Currently, the chipless RFID is a hot research topic with a huge applicability potential [5, 6]. Nowadays, the number of research groups and reported works are increasing continuously. However, it is uncommon to see reports specifically devoted to the area of printed chipless RFID tags on flexible substrates [3, 7, 8]. On these works applications on paper, as utilized for the production of banknotes, were introduced [7] as well as applications for item level tagging [8]. To the well knowledge of the authors, this is the first reported application of a fully printed chipless RFID within a safety system.

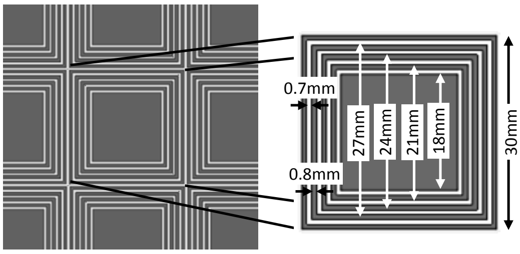
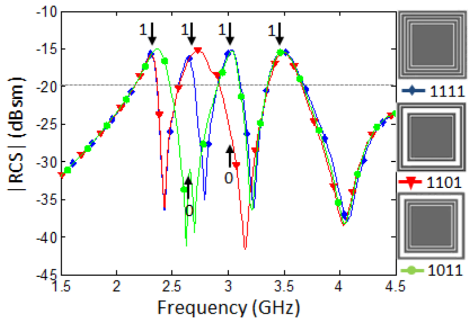


Fig. 2. Chipless RFID tag design and dimensions. On the left side, the infinite structure and, on the right side, the unitary element.



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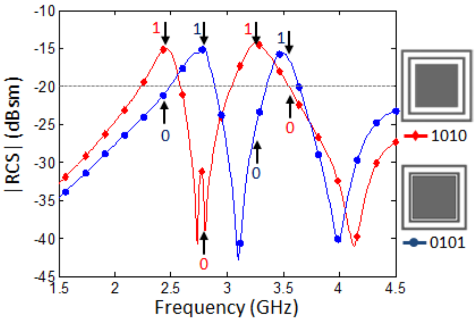

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Fig. 3. Simulated chipless RFID tags with different codes. a) tags with codes 1111, 1101 and 1011. b) tags with code 1010 and 0101. The dashed line represents the threshold.

Regarding the geometry, tags with concentric metallic shapes are found in [9, 14]. In the work of Vena et al [9], the authors use concentric circular rings to make a chipless tag. As a difference from the work introduced here, Vena's work does not use any periodicity in its designs. Other differences are related to the substrate material used to fabricate the prototypes, which is normally FR-4, a rigid substrate rather than a flexible one. On the other hand, the authors of this paper have recently reported some advances on the multi-tag reading procedures for this kind of systems in [14]. In this work, a novel methodology to identify simultaneously several circular-shape tags with same codification is introduced.

Some related work has been done regarding the FSS inspired chipless RFID tags. The work by Costas et al [10], deals with the idea to build a chipless RFID tag based on periodic structures. Specifically, Costa's work introduces a high impedance structure based on concentric squares. A high impedance structure implies to have a ground plane. Hence, the presence of both a ground plane and the use of

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Fig. 4. Measurement setup. a) inside the anechoic chamber setup [3], and b) outside the anechoic chamber.

FR-4 substrates are the main differences from the work introduced here.

III. REQUIREMENTS

The requirements defined for the development of the chipless RFID system under the eVACUATE project, includes the following aspects: Price of the tag, tag's production process, reader technology, maximum reading range and coding capacity.

The major restriction for the design of the chipless RFID system consists in the proposed price, which is intended to be less than one Euro cent per tag (± 30 cm² of area) in order to be competitive in the market. In order to achieve this goal, the application of a high throughput production process is required. In particular, the roll-to-roll processes are determined as the structuring methods to be applied [3].

By definition, the chipless RFID tag does not contemplates any IC or other SMD devices. The tag will be developed under the premise to be a flexible fully-printed device. The information is stored on the tag's geometry and, to extract the information of such tags, a reader based on radar techniques must be used.

The maximum distance to which the chipless RFID reader could successfully detect the chipless RFID tag is expected to be at least 1 m. In order to achieve this objective, the chipless RFID tags are specifically designed to accentuate the radar characteristics, i.e. the Radar Cross Section (RCS) feature since this parameter is directly related to the reading range of tag.

Last but not least, the chipless RFID system may be able to identify up to 8 different groups of persons crossing through a gate where the system is located. In technical terms, 8 groups could be codified using just 3 bits.

IV. TAG DESIGN AND CODING

The working principle of the designed tag is based in its RCS feature and is inspired in the RF behavior of the FSSs. A FSS is a spatial filter that is designed to let pass through it determined ranges of frequencies, rejecting the others. The FSS is a periodic structure composed by basic elements that are replicated along the available area. Therefore, the design efforts are focused in the development of this unitary element. The behavior of a complete infinite structure is approximated by properly setting the boundary conditions at the CAD model for this unitary element.

The idea behind the use of a periodic element is to take profit of the size of a bigger structure in terms of RCS. As a rule of thumb, the bigger the structure's area, the greater the RCS observed. A bigger RCS allows the system to increase the reading range where a backscattering signal could be detected. Reported maximum distances for chipless RFID

tags are in the order of cm [3, 8, 11-13], a bigger area could help to increase this range up to several meters. In fact, due to the implementation of the recommended structure, a reading distance up to 1.8 m is demonstrated.

On the other hand, a bigger tag implies a great effort on the design stage. With the help of FSS based systems, the design of a tag could be focused only in the design of the unitary element. A unitary element for the square-patch chipless RFID tag is shown in Fig. 2. Normally, the size of this unitary element is comparable with the size of a non-periodical-like tag.

This unitary element is composed by concentric metallic squares. In this structure each of the square rings represents a bit, and thus this tag could codify up to 16 IDs using 4 bits. The central solid square is used to improve the RCS response (by adding a notch at high frequencies) and does not represent any bit or information.

The square-shape does not only constitute the base of the periodical structure design, allowing the tag to significantly increase the reading range, but also introduces a degree of symmetry to the same. The symmetry causes the tag to be independent of the position with respect to the reader. This feature allows to recover the information regardless the rotation/tilt angle shown by the tag.

The sizes of square rings are correspondent to resonant structures in the band of 2 to 5 GHz. Hence, the bigger square ring is resonant in lower frequency and the small one is resonant at high frequency. Each unitary element is separate from each other by a distance of about 0.8mm.

Codification is based on the presence or absence of a determined square ring within the particular structure. Consequently, the presence of all four rings corresponds to the respective code 1111, where the MSB is related to the larger and the LSB to the smaller square ring. Each one of the bits are represented on the RCS feature as a frequency signature, where a 1 is associated to the presence of a peak at a determined frequency followed by a notch. The notches are used to determine whether the peak observed is valid or not, e.g. by using the expected phase jump associated to a resonant frequency the presence of the ring could be determined and the associated bit confirmed. The simulated frequency signature (magnitude of RCS) of the square-shape chipless RFID tag is shown in Fig. 3.

V. EXPERIMENTAL RESULTS

Measurements of square-shape tag are driven at both places: inside and outside the anechoic chamber, as shown in Fig. 4. A set of 8 different tags where measured. In order to corroborate the independence to position feature of the square-shape tags several tag's rotation angles (0, 45 and 90 deg.) are measured. Additionally, a tilt angle measurement is reported. Therein, it was found that the tag works up to an approximate tilt angle of 30 deg. The experiments are carried out with both, samples prepared on PET as well as on paper substrates. Thereby, no crucial impact of the particular substrate on the tag functionality is observed.

The complex RCS feature of square-shape tags (σ^{tag}) is calculated by following the procedures proposed by [9] by using the following equation:

$$\sigma^{tag} = \left[\frac{S_{21}{}^{tag} - S_{21}{}^{no-tag}}{S_{21}{}^{ref} - S_{21}{}^{no-tag}}\right]^2 \sigma^{ref} \qquad (1)$$

Where $S_{21}{}^{no-tag}$ is related to the measurement with empty anechoic chamber, or in case of measurements outside the anechoic chamber, the reading taken without tag. The $S_{21}{}^{ref}$ represents a reference value obtained from a defined

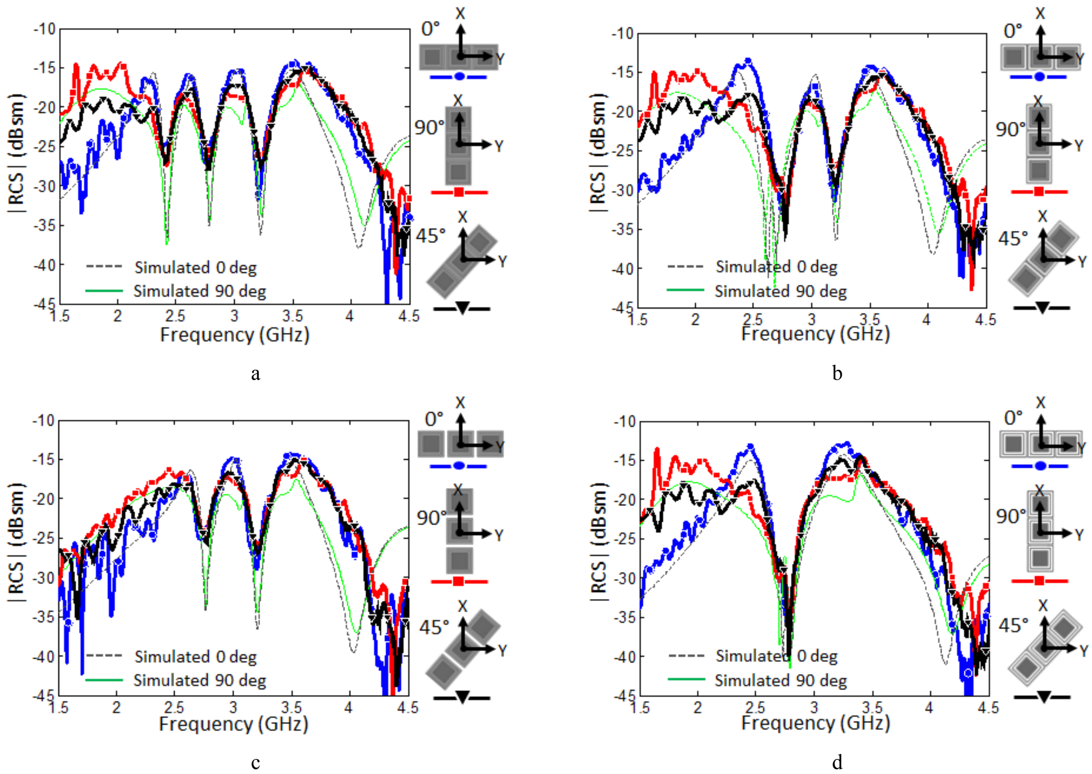

Fig. 5. Experimental results for chipless RFID tags measured in anechoic chamber setup for different rotated angles and codes. a) 1111, b) 1011, c) 0111 and d) 1010. The distance from Tx/Rx antennas to the tag is 1.8 m. Results for tags printed on PET.

measurement setup, in this case a square metallic plate of 50 × 50 mm. σ^{ref} corresponds to the theoretical (ideal) results obtained for the reference. All measurements are averaged 64 times before being saved (20 averaged samples for the second setup are used).

The anechoic chamber measurements are performed by using the PNA Agilent E8364B set to a -3dBm power level and two double ridged Horn antennas (1 to 18GHz) as Tx/Rx antennas are used. The measurements are reported at a distance of Tx/Rx antennas to the tag of 1.8 m. The feature consisting in the tag's positioning independence is also verified by using this setup and performing measurements with tags rotated 0 deg., 45 deg. and 90 deg. in X-Y plane. The good agreement between simulated and measured data for several coded tags and several rotated angles is observed in Fig. 5.

However, the results shown in Fig. 5 indicate that the observed behavior is not uniform among all the assessed rotation angles. This phenomenon is more obvious at lower frequencies as evident from the first peak observed below 2.5 GHz. This RF response asymmetry is due to the final aspect of the printed chipless RFID tag, which is not infinite in dimensions any more, but composed of just three unitary elements arranged in an array of 3 × 1. The final aspect of the measured tag and the rotation angle are shown in the inset in the same figure.

Similar measurements have been done for chipless RFID tags printed on paper substrates rather than PET. The measurements take place at the anechoic chamber and a distance of 80 cm is reported. In Fig. 6 the results obtained in this regard are shown. Note the shift in frequency observed on the paper substrate tags compared with PET ones. The shift in frequency corresponds to the increase in permittivity of the paper with respect to PET's.

Furthermore, tilt measurements for the square-shape chipless RFID tag are performed. For this setup, the tag is located at 0 deg. in the X-Y plane and a small tilt angle (θ) is added to the tag (towards Z and –Z axis). The distance from the Tx/Rx antennas to the tag is about 1 m. This configuration is exemplified in the inset in Fig. 7. The tilt angle (θ) is increased from 0 to 30 deg. in steps of 10 deg. The measured results show how it is still possible to identify the stored code from the tag unless a high degradation on the RCS response is observed.

The measurement setup implemented without using the anechoic chamber is shown in Fig. 4b. This setup is located at office and simulates a real working scenario with interferences and surrounding objects that add noise to the measurement. For this measurement setup a VNA Anritsu 37397D is used as well as the same horn antennas used in previous setup. The VNA is set to 0 dBm of power. The distance from chipless RFID tag to Rx/Tx antennas is set to 80 cm. Only tags oriented at 0 deg. are measured. The objective of this measurement is to corroborate this setup by comparison of the actual measurements against the ones performed at the anechoic chamber. As a result, in Fig. 8, the good agreement between both measurements for the square-shape tag is observed.

VI. Semi-Automatic Reader

The objective of this section is to introduce an evolution in the measurement procedure to optimize, simplify and expedite the measurement setup. The automation of measurements and decoding procedure is one of the goals pursuit into the eVACUATE project.

Normally, the measurement procedure implies to acquire several data samples from the observed tag between 20 and 64, depending on the laboratory equipment used for experimentation.

From our expertise, it is evident that this measurement procedure is time consuming and cannot be considered

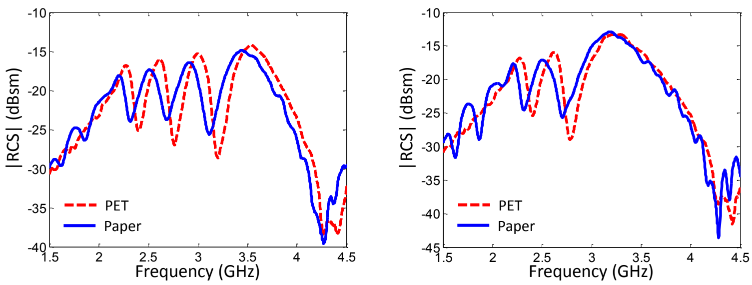

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Fig. 6. Measurement results obtained for tags printed over PET and paper. a) tag with code 1111, and b) tag with code 1101

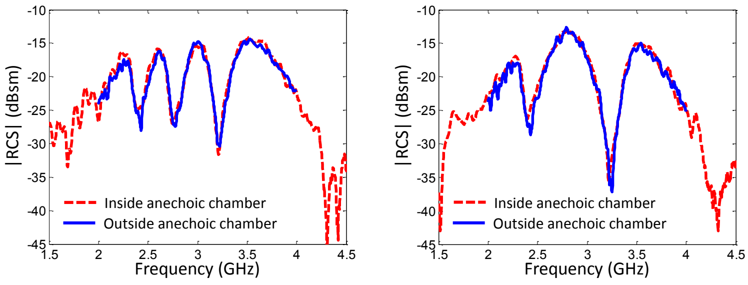

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Fig. 8. Measurement results obtained with the indoor setup. a) 1111 coded tag and b) 1011 coded tag.

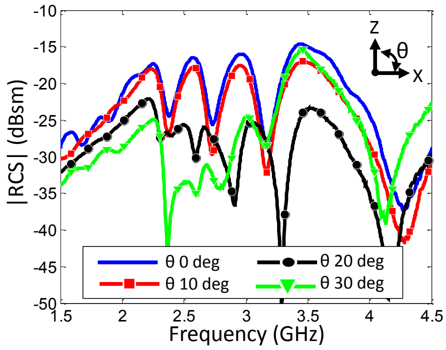

Fig. 7. Tilt angle measurements. Tilt angles varying from 0 to 30 deg.

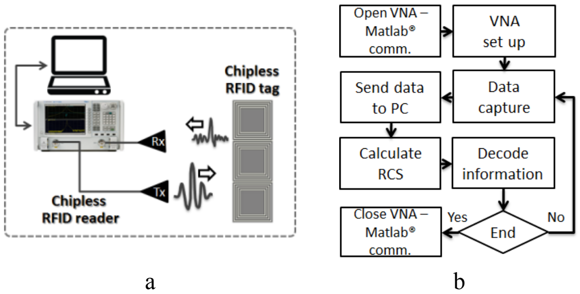

Fig. 9. a) VNA based reader schematic. b) Semi-automatic reader's algorithm proposed.

applicable in a real scenario. This is further supported by the discrepancy between the fact that tags are planned to be detected while passing through a gate and the estimated observation time of several seconds. Indeed, the measurement of just one tag using current methodology could take up to 5 min (standard case) making it inviable to use this procedure far from pure scientific purposes. Note that in similar works no information is provided at all for this reading processing time.

The methodology proposed herein makes use of automated procedures to recover the measurement data directly from VNA. This information is loaded into a script that calculates the tag's RCS and then decodes the information stored in it. This implementation is applied to the setup shown in Fig. 4b, using the VNA as reader. The VNA based reader schematic is shown in Fig. 9a. The data is collected through the VNA's Ethernet interface controlled by using a MATLAB® script. The empty measurement and the reference RCS measurement need to be loaded beforehand.

The script initializes the VNA-MATLAB connection and then configures the VNA to display the captured data in the required format. Once the setup finished, the script triggers a port measurement and waits till frequency sweep ends. Following, the data is sent to PC and processed, providing the data in a suitable format for further steps. Next, the complex RCS is calculated by implementing eq. (1). Finally, the decoder sub-routine is called and the code is displayed as well as the |RCS| and phase information of the read tag. A flow diagram of proposed algorithm is shown in Fig. 9b.

In order to speed up this reading procedure, only one frequency sweep data set is used, i.e. the average of 20 or 64 samples per measured sample is not used any more. Results obtained by using this procedure corroborate that it could be possible to use just one measurement (a complete sweep) to calculate the complex RCS and recover the information from the tag. By doing so, the total time needed for a single measurement is drastically reduced from several minutes to just a few seconds (about 3 to 4 s). Note this time is dependent on the total sweep time of VNA. In our case for an Anritsu VNA, 1601 sample points and an IF bandwidth frequency of 1 kHz is used. This methodology was successfully tested for different tags far from square-shape tags, e.g., using tags reported in [3] and [14].

VII. CONCLUSIONS

We have introduced a new square-shaped chipless RFID tag, which is designed on the basis of FSS design methodologies. The tag is created to fulfill the requirements, established in EU FP7 project eVACUATE for applications in citizen's security and crisis events. The fabrication of the tag is compatible with mass production techniques and does therefore comply with the intended low costs per tag, as required for a realistic application of the technology. The experiments have further proved the possibility to use flexible, low cost substrates, such as PET and paper, which further represent typical substrates available at the dedicated venues. In addition to the measurements at anechoic chamber, an additional setup is utilized, corroborating a realistic working scenario. During the measurements, a maximum reading range of 1.8 m is determined. Moreover, by measuring several rotation and tilt angles, the independence from the position feature of the square-shape chipless RFID tags is shown. Finally, a novel optimized methodology to reduce the per tag decoding time is proposed.

VIII. ACKNOWLEDGEMENTS

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