Chipless RFID Polarimetric Radar Barcodes Encoded by Dipole Scattering Domains

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ABSTRACT Recently, a novel chipless radio-frequency identification (RFID) concept based on polarimetric radar barcodes was introduced. These tags are similar to the well known optical quick response codes (QR codes). In polarimetric radar barcodes the information is stored as polarimetrically coded areas arranged in a grid and read out by an imaging radar. This paper presents a novel concept for elegantly creating polarimetric barcodes based on dipole scattering domains. Each scattering domain consists of several hundred dipoles. The dipoles are either uniformly arranged at a specific angle, which produces a specific angle-dependent polarization response, or randomly oriented to produce an unpolarized response. In order to read out the polarimetric information stored in the tags, the position and rotation of the radar barcodes needs to be determined. Our research reveals that using three reference elements and a novel decoding algorithm, a position- and rotation-tolerant readout is possible. To reduce distortions caused by the surface of the structure carrying the dipoles, different matching layer concepts were investigated. The novel chipless RFID tag concept is tested using a fully polarimetric W-band (75-110 GHz) imaging radar. The implemented setup allows for a theoretical data capacity of 1.92 bit/cm² on a single layer PCB. In our measurements, we achieved a data capacity of 1.52 bit/cm². Utilizing the chosen tag size of 45 mm × 45 mm resulted in a tag with a greater than 30 bit data capacity, which is an excellent value for chipless RFID.

INDEX TERMS Chipless radio-frequency identification (RFID), image processing, millimeter wave, radar imaging, RFID.

I. INTRODUCTION

Radio-frequency-identification (RFID) applications are becoming a part of every aspect of the modern world (e.g., smart warehouses [1], security [2] and industrial applications [3]). In areas where power supply is challenging or in harsh environmental conditions, chipless tags provide options for labeling objects. These tags are often limited in their information content or information density. Another concern is the robust reading procedure. Common approaches can be categorized into time- and frequency-domain methods. Time-domain methods frequently utilize time-domain reflectometry (TDR), either via electro-magnetic (EM) or surface acoustic waves (SAW). The total amount of encoded bits is equal to the number of possible reflection points. Phase modulation can also be applied to the scheme [4]. In the frequency domain, information is encoded via the excitation of resonant structures [5], [6]. Here the tag capacity is limited by the available frequency range and the separability of the resonances. As a third option, image-based methods have been examined; there the tags are illuminated by an EM-wave from a spatially high-resolution imaging radar system. The information is then retrieved from reconstructed radar images. As a basic approach, the presence or absence of a reflector was used to store information [7]. With the use of a polarimetric radar, backscattering structures were introduced in [8] which provide unique polarization and phase information. The approach presented in [9] utilized the angular position of small wires placed in multiple layers to encode information.
A concept for a tag/imaging reader system is shown in Fig. 1. The reader can be realized as a multiple-input multiple-output (MIMO) radar [10] or by using an antenna moving along a plane to span a synthetic aperture [11]. The measured radar signals are used to determine the reflectivity of the objects in the volume or plane of interest. With the use of common strategies, such as broadband holography and backpropagation [12]–[14] of the measured electrical fields, focused images can be created. These can then be used to decode the encoded tag symbols.

In [15], a novel approach using known polarimetric backscattering structures was presented. The tag was interrogated by a fully polarimetric signal, resulting in the complete polarimetric backscattering information [16]. This paper presents a novel approach to polarimetric RFID-concepts. The compact tag structure made of simple and well-known structures has an information content of 1.52 bit/cm². A matching layer is applied to it, which limits the amount of mirroring effects, therefore making the tag more robust in the reading process.

The rest of the paper is organized as follows. First the tag concept as well as the design considerations with the underlying theoretical polarimetric radar imaging background are introduced in Section II. In Section III, the evaluation algorithm is presented on the basis of simulations. Also, the theoretically distinguishable number of symbols is determined. Finally, in Section IV, the feasibility of the proposed concept is experimentally demonstrated.

II. TAG CONCEPT AND DESIGN CONSIDERATIONS

The novel approach presented here is based on dipole scattering domains. These are either regions of a polarized backscattering response of randomly equally distributed dipoles, called code elements, or regions of an unpolarized behavior from randomly oriented, equally distributed dipoles, called reference elements. Each of the regions of the tag shown in Fig. 1 is filled with numerous dipoles that have a well-defined backscattering behavior. The tag has three reference elements, which serve for position detection. The structure of a tag encoded in our approach is shown in Fig. 2. Hereafter, the design considerations resulting in this tag structure are presented.

The tag design should fulfill a number of properties, that is, a small tag size, low cost, a distinct scattering pattern and a high data capacity. The modular tag structure of [15] is generally well suited to deliver a flexible and high-performing encoding scheme. Thus, the tag proposed here consists of several scattering domains, each of which possess a distinct scattering behavior (Fig. 2). Scattering domains used as code elements function as a carrier of information, whilst reference elements are used to give insight to the rotational displacement of the tag. To result in a high data capacity, the number of possible distinguishable encoding states should be as high as possible. Generally, the tag capacity $I$ in bits for the modular design is [15]

$$I = -n_e \log_2 \left( \frac{1}{n_s} \right)$$

(1)

with $n_e$ representing the number of code elements and $n_s$ the number of distinguishable code symbols. For the latter, a defined scattering process per code element is needed. In general, an object’s full scattering behavior can be determined using two polarimetric orthogonal interrogation signals, that is, two orthogonal polarization directions, also known as the polarization basis. The scattering process can be described by the scattering or Sinclair matrix $\mathbf{S}$ [16]

$$\mathbf{S} = \begin{pmatrix} \sqrt{\sigma_{11}} e^{j \phi_{11}} & \sqrt{\sigma_{12}} e^{j \phi_{12}} \\ \sqrt{\sigma_{21}} e^{j \phi_{21}} & \sqrt{\sigma_{22}} e^{j \phi_{22}} \end{pmatrix}.$$  

(2)

The terms $\sigma_{tq}$ describe the radar cross section (RCS) for the respective polarization combination $tq$, with $t$ denoting the polarization at the receiver and $q$ the polarization of the incident electro-magnetic (EM) wave; $\phi_{tq}$ describes the
TABLE 1. Canonical Scattering Matrices in HV-Basis [16]

| Planar surface                  | $\mathbf{S} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ |
|--------------------------------|---------------------------------------------------------------|
| Dipole                         | $\mathbf{S}(\gamma) = \begin{pmatrix} \sin^2(\gamma) & -\frac{1}{2}\sin(2\gamma) \\ -\frac{1}{2}\sin(2\gamma) & \cos^2(\gamma) \end{pmatrix}$ |
| Dihedral reflector             | $\mathbf{S}(\gamma) = \begin{pmatrix} -\cos(2\gamma) & -\sin(2\gamma) \\ -\sin(2\gamma) & \cos(2\gamma) \end{pmatrix}$ |
| Left-hand / right-hand helix   | $\mathbf{S} = \begin{pmatrix} 1 & \mp j \\ \mp j & -1 \end{pmatrix}$ |

The corresponding phase terms. The scattering process is described compactly via

$$E_s^{\parallel} = \frac{e^{-jk\rho}}{\sqrt{4\pi k\rho}} \cdot \mathbf{S} \cdot E_r^{\parallel} = \frac{e^{-jk\rho}}{\sqrt{4\pi k\rho}} \cdot \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \cdot E_r^{\parallel},$$

(3)

with the Jones vectors of the scattered and incident field $E_s^{\parallel}$ [13], the distance of the object to the receiver $r$, and the wave number $k$. The polarization basis of the Jones vectors is elementary for correct interpretation of the scattering process. For simple objects — the so-called canonical scattering processes — the Sinclair matrix is fully known [16]. These objects are therefore well suited to be used in the design of complex structures and are at the core of the tag design. The Sinclair matrices for the canonical scattering objects are shown in Table 1. In the matrices, the parameter $\gamma$ describes the rotation of the object around the radar line-of-sight and is unambiguous for values between $-90^\circ$ and $90^\circ$, with $0^\circ$ being aligned with the vertical axis. The polarization basis for the scattering matrices is the linear horizontal-vertical polarization. When a matrix in a known basis is available, this matrix can be transformed into every other polarization basis [16]. When choosing the scattering behavior for the code elements, utilizing a canonical scattering process is sensible. Selecting one of the canonical scattering processes as a design base for the tag serves as a method of ambiguity control since it is unique from the others and allows for an optimized evaluation algorithm. The chosen structure should be relatively easy to manufacture, e.g. on a single layer PCB. When comparing the basic structures in Table 1, the dipole scattering mechanism acts as a suitable possibility for encoding symbols since the Sinclair matrix is only dependent on the angular orientation of the dipole. Therefore, the maximum amount of symbols is determined by the capability of the imaging system and the evaluation algorithm that estimates the orientation angle $\gamma$ of the dipole. From the other basic structures, only the dihedral offers the same possibility but it is harder to manufacture since it requires a depth component, whereas the dipole can be put on PCB. Therefore, as the basic components of the tag, dipoles were chosen.

The other design variable derived from (1) is the number of code elements $n_e$. As this is limited by the available tag size, a general design rule can be derived from the measurement system’s lateral resolution. It can be determined through [14]

$$\delta_{\text{lat}} \approx \frac{\lambda}{4\sqrt{D^2 + L^2}} + 1,$$

(4)

where $\lambda$ is the wavelength, $D$ the distance between the target and aperture plane, and $L$ is the effective aperture length. This serves as a lower bound to the encoded structures of the tag. In broadband systems, evaluating (4) for the center frequency gives an approximation to the lateral resolution of the imaging system. The tag is organized in a grid-like structure, as shown in Fig. 2. This allows a standardized scattering domain size, which is helpful in tag design and information retrieval. In order to increase the robustness of the imaging process and avoid cross-talk between encoded symbols, it is sensible to use more than one resolution cell as a code element. The scattering domain extents were chosen as such, that for $D \approx L$ at a frequency of 92.5 GHz, there would be approximately 8 resolution cells per domain. This results in a scattering domain size of 15 mm × 15 mm. In a domain that is used as a code element, all dipoles have the same direction and, therefore, angle.

Since the tag is interrogated by an imaging radar, each resolution cell of a scattering domain should behave the same as the others. As a result, multiple dipoles were distributed uniformly over each scattering domain. The size of each dipole was chosen to be 500 μm × 100 μm. This ensures that a standard manufacturing process is possible and also allows for a wide directivity with the length of approximately $\lambda/6$, at a frequency of 95 GHz.

The number of dipoles per scattering domain is the last design parameter. There has to be a significant amount of dipoles to ensure that the resolution cells are filled. It is useful to randomly place the dipoles in the domain, as this avoids an interference pattern of the combined scattering response. When placing them, each dipole should be turnable and not overlap with another. The dimensions of the scattering domain and the dipoles limit the total number that can be randomly placed. Using 200 dipoles per scattering domain, still multiple random distributions can be found. Lower numbers decrease the radar cross section (RCS), which would in turn decrease reading range. As such, the number of dipoles per domain was chosen to be 200.

In [15], reference elements were placed at three corners to detect the orientation of the tag. There, plane surfaces were used. This results in problematic behavior if the tag is not oriented perpendicularly to the radar line-of-sight, as on plane surfaces specular reflection occurs and results in the possibility of undetected surfaces. The dipole structure offers a suitable solution for the reference elements as well. An advantage over different structures is the amplitude of the backscattering response naturally being in the same order of magnitude than the coding elements. In reference elements the dipoles are not only distributed randomly but are also oriented randomly. This will be further explained in the following section.

The grid is chosen to be $3 \times 3$. The standard tag orientation is in such a way that the reference elements are placed at
three corners exclusive the bottom right corner. In this configuration, the dipoles are oriented in their desired angle. The encoded angles of the dipole scattering domains of the tag shown in Fig. 2 are listed in Table 2. In total, this tag has a footprint of 45 mm × 45 mm.

III. SCATTERING DOMAIN DECODING CONCEPT

For a useful decoding scheme, the distinct backscattering behavior needs to be mapped onto the symbols of the used alphabet. Also, the maximum quantity of symbols that can be decoded needs to be determined. Therefore, we devised an evaluation algorithm to decode the orientation angle of each scattering domain and tested its performance on simulated data. Since the backscattering behavior of a dipole is well known, the evaluation algorithm is designed on exploiting this. It is possible to form a Sinclair matrix for each voxel of the reconstructed volume. As an example Fig. 3 shows the reconstructed images of the aforementioned tag at the simulated range gate. Each scattering domain can be identified; for example, element 5 has only strong backscattering behavior in the $S_{HH}$ component, which aligns with the theoretical description. Analogously elements 4, 6, and 9, which are oriented in $\pm 45^\circ$, turn the polarization of the signal and therefore create stronger responses in the crosspolarized components $S_{HV}$ and $S_{VH}$. Similar conclusions can be drawn for each scattering domain. The main part of the algorithm consists of a correlation of the Sinclair matrices of the voxel that contain the tag, with the theoretical formulation of the Sinclair matrix for a dipole. Combined with a maximum search the decoded angle $\hat{\gamma}$ results to

$$\hat{\gamma} = \max \left\{ \| S_{\text{Meas}} \circ S_{\text{Dipole}(\gamma)} \| \right\} \quad \forall \gamma.$$  \hspace{1cm} (5)
where \( \odot \) denotes the Hadamard product of \( S_{\text{Dipole}}(\gamma) \), being the matrix from Table 1, and \( S_{\text{Meas}} \), the measured Sinclair matrix for each voxel.

The area of the tag is identified from the available fully polarimetric information. Therefore, the maximum of the matrix components are summed up for each \( x \)- and \( y \)-position and compared to a threshold. With the knowledge of the shape of the tag, an area can be identified. If more objects are present in the volume, the volume needs to be split up, so that only one object remains present. The tag’s distance can be determined via maximum search along the \( z \)-axis (depth direction). With this, the tag’s voxels are identified.

In a next step, the position of the reference elements must be determined, to offset a potential rotation. Having full polarimetric information of an object allows for a change of the polarization basis according to [16]

\[
S(H',V') = U_2(\phi)^T \cdot S(H,V) \cdot U_2(\phi)
\]  

with

\[
U_2(\phi) = \begin{pmatrix}
\cos \phi & -\sin \phi \\
\sin \phi & \cos \phi
\end{pmatrix}
\]  

being the rotation matrix around the radar line-of-sight, whereas \( S(H',V') \) is the Sinclair matrix in the new basis. This rotation can be interpreted as a rotation of the dipoles resulting in the specified behavior of the Sinclair matrix in Table 1. When multiple dipoles of different angle contribute to the scattering (e.g., being in the same resolution cell) the resulting scattering response will be more constant for a polarization base rotation. The combined dipole response can be thought of as an average over all existing dipole angles in this resolution cell. Since the dipole angles are uniformly distributed and, therefore, not fully orthogonal, a preference in excitation angle is still to be expected. In Fig. 4, this is shown for a resolution cell in the center of a reference element and a code element respectively. The reduced amplitude of the reference element is clearly visible. Using this, the corner that has the highest amplitude along the rotation axis can be identified. Since three corners contain the reference elements, only the highest value is a code element. With the knowledge of the reference elements, the positions of the code elements are therefore, defined, as they are positioned along the grid. The offset angle \( \gamma_{\text{rot}} \) can be calculated using the reference elements. After the central reference element is identified and virtual lines are drawn to the center of the other reference elements, an angular displacement to the horizontal and vertical axis can be determined. These values are averaged, and \( n \cdot 90^\circ \) is added, with \( n \in \{0,1,2,3\} \) depending on the corner that the central element is now closest to.

For each voxel, \( \gamma \) is now calculated according to (5), and a mean value of the center voxel for each code element determines the final decoded angle. This results in a more stable decoding since edge voxels of each scattering domain are not considered. As a last step, the offset angle \( \gamma_{\text{rot}} \) is subtracted.

The simulation was done in FEKO, where the dipoles were illuminated from a plane wave source with horizontal respectively vertical polarization and amplitude 1 V/m. The backscattered fields were saved and split up into their vertical and horizontal components. These fields were then backpropagated from the field detector plane to the tag plane. In order to evaluate the decoding performance, one single code element is simulated whilst the encoded angle of the dipoles is changed in \( 1^\circ \) steps. The angle is determined using the described algorithm, without the steps of tag and reference element detection. The resulting decoding is shown in Fig. 5. The normalized histogram of the absolute deviation of the decoding is depicted in Fig. 6. It can be seen that the error is mostly concentrated close to 0. The maximum difference between the encoded angle \( \gamma \) and the decoded angle \( \hat{\gamma} \) resulted to \( 0.917^\circ \). The standard deviation \( \sigma \) of the decoding
amounts to 0.232°. The step size between the symbols was chosen conservatively to avoid false estimations, which would necessitate an additional error correction step. It was set to 2°, which is greater than both 6σ and twice the maximum absolute deviation. Thus, the theoretical number of distinguishable symbols results in 89. As a result, the theoretical tag capacity I is 38.85 bit, and the information density for a 45 mm × 45 mm sized tag is 1.92 bit/cm². In real measurement scenarios diminishing factors such as noise and antenna position errors must be accounted for, as well as the combined scattering of the different domains at their respective edges.

Afterwards, the simulated tag response shown in Fig. 3, was decoded. Fig. 7 shows the resulting decoding for each voxel of the tag for the simulated tag. Each scattering domain is clearly visible and, in the reference elements, multiple angles are assumed, which is reasonable, since the angular distribution of these dipoles is uniform. Accordingly, the mean angle for each resolution cell is the superposition of multiple dipole angles, which results in an arbitrary angular value. Since the reference elements are detected before the decoding stage, the resulting angles of those scattering domains do not carry information and are shown just for comprehensiveness. In Table 3, the encoded angle γ is compared to the decoded angle ̂γ. The decoding is seen to be accurate, and the angles are determined with a maximum absolute error of 3.67°. This is higher than the maximum deviation for a single code element. As the element is no longer in the center of the simulated area, the illumination is different than before, which might result in this deviation.

IV. MEASUREMENTS
For experimental verification of the proposed concept, several measurements were performed. They were performed on a test bench that allows fully polarimetric combinations of transmitter and receiver antennas. The antennas are horn antennas connected via frequency extenders to a network analyzer (NWA). The measurement scenario is shown in Fig. 8. The frequency extenders are hidden behind the absorber material to reduce the amount of reflections from the test bench.
FIGURE 9. Measured tags with different matching layer: left: teflon foil, right: 3D-printed polypropylene layer.

The antennas are moved using stepper-motors along a 2D-trajectory and thus, create a 2D-aperture. For each point of the aperture, 401 equally spaced frequency points were acquired. This yields a sufficiently high correlation gain to distinguish the tag from the noise floor. Further information on the measurement setup can be found in [17]. The interrogation signal is a stepped frequency continuous wave (SFCW) signal from 75 GHz to 110 GHz. This results in a range resolution of $\delta_r \approx 4.3$ mm. The aperture in the $x$- and $y$-directions was set to 18 cm and 10 cm, respectively. It was chosen to illuminate two tags positioned next to each other, as shown in Fig. 9. The distance between the aperture plane and the tag was 28.8 cm. This resulted in lateral resolutions of $\delta_{lat,x} \approx 2.72$ mm and $\delta_{lat,y} \approx 4.74$ mm. This difference in resolution is caused by the difference in $x$- and $y$-apertures. In a real-world industrial measurement setting, the test bench would be replaced by a specifically designed (hand-held) reader, which in general would have a square aperture to yield equal resolution in both directions. As each fully polarimetric measurement with the test bench takes currently around three hours, this could also be reduced to the order of magnitude of several milliseconds with a specific reader (e.g. personal security radar systems with 3000 Tx and 3000 Rx antennas, where the entire imaging process lasts 1-2 seconds [18]).

The tags are mounted on a styrofoam to reduce unwanted reflections from the surrounding. For calibration purposes, two measurements per polarization were carried out. The first was an empty space measurement $s_{ES,tq}$, which removes the coupling of the antennas. The second was a measurement of a dihedral reflector $s_{DH,tq}$, with its known reflectivity behavior $r_{DH,tq}$. The dihedral is positioned at $0^\circ$ for the copolarized channels and at $45^\circ$ for the crosspolarized channels. This removes the effects of the combined channel response of the used Tx- and Rx-antennas. As a result the measured signal after calibration is [15], [19]

$$s_{cal,tq} = s_{tq} - s_{ES,tq} - r_{DH,tq}.$$

In a potential practical reader-system, the calibration procedure could be done during an end-of-line test after production of the reader (and the calibration data can be stored in the reader). Unlike the present laboratory setup, of course, only a one-time calibration is necessary in a product-ready integrated radar system.

The calibrated signals are then reconstructed in the tag plane. Fig. 11 shows the normalized $S_{HH}$ for both tags. The tag with the 3D-printed layer has a very high amplitude along the edges of the matching layer, but appears to be uniform over the relevant dipole area. On the left tag, the middle element

FIGURE 10. Measured tag without the matching layer (dotted lines just for emphasis).

FIGURE 11. Normalized reconstructed image in $S_{HH}$ of the measured scene.
is visible even in this scaled view. The other elements appear to be of roughly the same amplitude, with elements 2 and 8 having reduced levels, which matches the encoded structures in principle. On further evaluation, the right tag does not show the wanted information and a retrieval of the encoded dipole angle is not possible. This might be due to an increased surface roughness of the 3D-printed layer or a mismatch in the dielectric properties of the matching layer. The left tag shows the expected backscattering behavior, as shown in Fig. 12. Even though the surface roughness of the matching layer may provide an alteration of the polarimetric response of the tag there as well, this effect could not be observed. This would particularly show in the cross-polarized components of the plane tag border. As this behaves unobtrusively, we assume the effect of the matching layer concerning surface roughness to be negligible. Generally, the tag structure is visible, but the elements are not as uniform and equivalent in their amplitudes in comparison to the simulations. This is possibly due to noise, which corrupts the reconstructions. Additionally, the peak value of the $S_{VV}$-component is reduced. This is likely caused by a slight difference in the gain of the horn antennas. Changing temperatures during the measurement may also contribute to this, as it would decrease the effectiveness of the calibration.

The reconstructed signals are evaluated using the decoding algorithm, and the angle for each tag voxel is shown in Fig. 13. The decoded angles for the elements are listed in Table 4. There is an outlier with an absolute error of 13.44°; this might be accounted for by an air gap between the matching layer and the tag, as the matching layer was applied manually.

### TABLE 4. Decoded Angles From Measurement Data in Comparison to the Encoded Angle

| Element | Decoded angle $\hat{\gamma}$ | Encoded angle $\gamma$ |
|---------|-------------------------------|-------------------------|
| 2       | $-1.45^\circ$                 | $0^\circ$               |
| 4       | $+58.44^\circ$                | $+45^\circ$             |
| 5       | $-87.27^\circ$                | $\pm 90^\circ$          |
| 6       | $-43.67^\circ$                | $-45^\circ$             |
| 8       | $-1.11^\circ$                 | $0^\circ$               |
| 9       | $+46.94^\circ$                | $+45^\circ$             |
resulting in local minor imperfections. Nevertheless, the effect requires further investigation. Otherwise, the maximum absolute error is 2.63°, which is slightly decreased in comparison to the maximum absolute error of 3.67° for the simulated tag. The effect is surprising, as influences such as noise and temperature drift would be detrimental to the decoding; however, this does not seem to be the case.

The current approach serves as a lower bound on the accuracy of the decoding, as a more stable manufacturing process can possibly eliminate the occurrence of air gaps and folds in the teflon foil. Consequently a uniform distribution of symbols with a distance of 5° is reasonable. This results in an information capacity of 1.52 bit/cm². In the encoding procedures some sort of error detection code would increase the tag robustness.

As the decoded angle ˆγ is reasonably stable over the scattering domains and the edge between the different elements does not seem to be corrupted, a decrease in domain size is possible, further increasing the tag capacity.

V. CONCLUSION

We presented a new method of creating image-based RFID-tags exploiting dipole scattering via a fully polarimetric measurement setup. The information is encoded in the angular directions of dipoles of different regions. A decoding algorithm was specifically designed using the known scattering behavior of the dipole structure. This resulted (for this tag geometry) in a theoretical data capacity of 38.85 bit. A tag was manufactured and equipped with a matching layer to prevent specular reflections. The measurement was consistent with the theoretical and simulation results, despite irregularities in the matching layer distorted some results. Further investigation concerning the size of the scattering domains must include a more stable manufacturing process concerning the matching layer; however, this seems as a promising way to increase data capacity.

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