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Signal space representation of chipless RFID tag frequency signatures

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***Abstract*—A novel approach to decode information in a chipless RFID tag using signal space representation (SSR) is presented. SSR represents 2^b possible tag signatures of a b-bit tag as linear combinations of a small set of L orthonormal basis functions. Each signature encoding a binary bit sequence is represented by a point in an L-dimensional constellation. Prototype 3-bit chipless RFID tags are used to validate the detection technique. The proposed method gives a solid mathematical framework to develop detection and decoding methods for more complicated tag reading scenarios.**

***Index Terms*—chipless RFID, spiral resonator, signal space representation.**

I. Introduction

Radio frequency identification (RFID) is one of the most prominent technological advancements in modern times that has steadily permeated into all aspects of modern human society. Its applications vary from inventory control to finance and medicine [1]. RFID technology enables automatic and wireless communication of information which serves as an attractive alternative to many existing information tagging techniques such as 1D and 2D optical bar-codes in a multitude of applications. However, the cost of chipped RFID tags has hindered the use of RFID technology in applications involving large scale item tagging where optical bar-codes are still being widely used, e.g. in library management systems, the retail industry and logistics [2], [3].

Recent advances in chipless RFID technology [3] have led to the production of extremely low cost tags. A chipless RFID tag is simply a passive reflector of an interrogation signal emitted by an RFID reader. It relies on material and structural properties to encode information which is embedded in the reflected electromagnetic radiation as a frequency signature [4]–[6] or abrupt phase alterations [7] or delays in time of arrival [8]–[10]. Research has recently focused on the development of novel chipless RFID tags which are more compact and are able to encode more bits of data [5]. However, not much work has been done on developing algorithms for detection and decoding of encoded data.

Most of the chipless RFID designs found in the literature are based on frequencies beyond the S-band (above 2 GHz) [3]–[6], [9], [11]. Hence, minute structural inconsistencies and imperfections (in mass scale production) of these chipless RFID tags yield errors and distortions in the expected tag performance. Also, commercial production of chipless tags requires the use of printable conductive inks having a lower conductivity than pure copper or silver. This lower conductivity would not yield the desired performance. To address these problems detection algorithms need to be developed, which are able to detect tag signatures and accurately decode their data amidst distortions and additive noise.

In [12], [13] chipless RFID reader designs are presented which utilize threshold based detection aided by calibration values for extracting data bits from chipless RFID tags. However, since these approaches are based on fixed thresholds, they do not have the flexibility required in the detection process to address the effects caused by the error sources. Hence, more work is required in order to achieve detection algorithms which can combat these sources of detection error.

This paper presents a mathematical model for the detection of chipless RFID tags based on signal space representation (SSR) [14] of tag frequency signatures. Here, the frequency signatures from tags are represented as signal points in a signal space, and detection is based on minimum distance detection. This approach in detecting signals is widely used in mobile and broadband wireless communication systems, where high speed data is reliably decoded in highly dynamic and fast fading multi-path wireless environments which adversely distort and disperse the transmit data signals [15]. To the best of our knowledge, an SSR based approach for detection has not been considered in the context of chipless RFID. The main contrast between a conventional wireless communication system and a chipless RFID system is in the sources of signal impairment where the noise behavior due to imperfections in the fabrication of the chipless tags plays an important role.

The remainder of this paper is organized as follows. In Section II the proposed mathematical framework is presented. The next section details the design, fabrication and operation of a prototype 3-bit tag used for validating the mathematical model. Section IV presents a discussion on the experimental results. Finally conclusions are drawn in

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Section V.

II. Signal space representation of tag frequency signatures

This section presents the proposed detection method based on the SSR of the different tag frequency signatures. A set of orthonormal basis functions, which are capable of accurately describing any of the possible tag signatures, are formulated.

Given the tag is designed to represent b bits, there are $n = 2^b$ possible different tags. Let's assume that each tag signature is analyzed in the frequency domain with m frequency samples. These n independent tag signatures $\mathbf{h}_k, k = 1, \ldots, n$ (normalized to having unity power) each having m samples form a matrix H

$$\mathbf{H} = \ [\, \mathbf{h}_1\ \mathbf{h}_2\ \mathbf{h}_3\ \cdots\ \mathbf{h}_n \,] \tag{1}$$

Singular value decomposition of H yields,

$$\mathbf{H} = \mathbf{U}\ \mathbf{\Sigma}\ \mathbf{V}^T \tag{2}$$

where $\mathbf{U}$ and $\mathbf{V}$ are unitary matrices composed of orthonormal column vectors $\mathbf{u}_i$ and $\mathbf{v}_i$, respectively. $\mathbf{\Sigma}$ is a diagonal and positive definite matrix which is called the singular value matrix containing singular values σ_i. If $\mathbf{H}$ has rank r it will contain r non-zero singular values. Since the $\mathbf{H}$ is composed of n independent tag signatures $r = n$. Therefore, (2) can be re-written as,

$$\underset{m \times n}{\mathbf{H} = [\, \mathbf{u}_1\ \cdots\ \mathbf{u}_n \,]} \underset{n \times n}{\begin{bmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \\ \cdot & \cdot & \cdots & \cdot \\ 0 & 0 & \cdots & \sigma_r \end{bmatrix}} \underset{n \times n}{\begin{bmatrix} \mathbf{v}_1^T \\ \cdot \\ \cdot \\ \mathbf{v}_n^T \end{bmatrix}} \tag{3}$$

Further simplification of (3) gives the inner product between vectors $\mathbf{h}_k$ and $\mathbf{u}_i$, i.e. $\langle \mathbf{h}_k, \mathbf{u}_i \rangle = \mathbf{h}_k^T \mathbf{u}_i$, as

$$\mathbf{h}_k^T \mathbf{u}_i = \sigma_i v_k^i \ , \tag{4}$$

where v_k^i is the k-th element in the column vector $\mathbf{v}_i$. Therefore, we can write,

$$\mathbf{h}_k = \sum_{i=1}^{n} \langle \mathbf{h}_k, \mathbf{u}_i \rangle\ \mathbf{u}_i = \sum_{i=1}^{n} \left(\sigma_i v_k^i \right)\ \mathbf{u}_i \ . \tag{5}$$

Since only a handful of σ_i are prominent and the rest are negligible each $\mathbf{h}_k$ can be approximated using a few $\mathbf{u}_i$ [16], [17] , i.e.

$$\mathbf{h}_k \approx \sum_{i=1}^{L} \langle \mathbf{h}_k, \mathbf{u}_i \rangle\ \mathbf{u}_i = \sum_{i=1}^{L} \left(\sigma_i v_k^i \right)\ \mathbf{u}_i \ \ ; L << n \ . \tag{6}$$

Hence, u_i , $i = 1, 2, \ldots, L$ serves as a basis for each tag signature $\mathbf{h}_k$. This will enable the construction of an L dimensional signal space $\mathcal{S}$ where the 2^b tag signatures $\mathbf{h}_k$ are represented as 2^b signal points $\mathbf{s}_k$ where

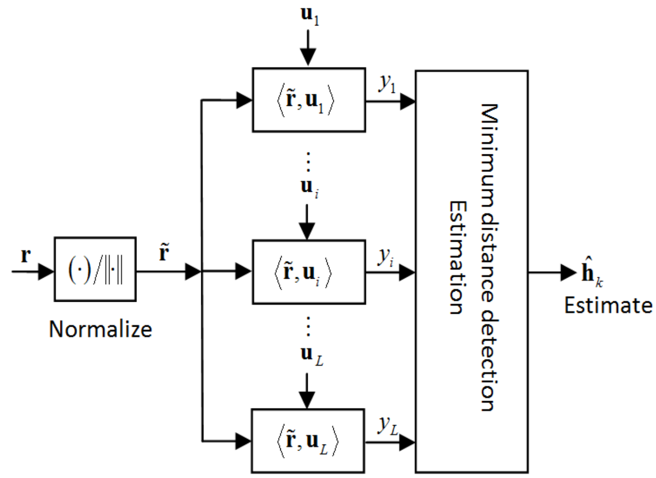


Fig. 1. Block diagram of the receiver processing

$$\mathbf{s}_k = \left[s_1^k, \cdots, s_L^k \right] \ \text{with}\ s_i^k = \langle \mathbf{h}_k, \mathbf{u}_i \rangle \ . \tag{7}$$

These 2^b signal points will serve as a signal constellation $\mathcal{C}$ and aid in the detection of the measured unknown tag signature through minimum distance detection. Let $\mathbf{r}$ denote a measured tag signature by the RFID reader which is affected by pathloss, noise and undesirable effects due to fabrication errors. Fig. 1 illustrates the decoding process involved at the receiver. Here, the inner products between the normalized $\mathbf{r}$ (i.e. $\tilde{\mathbf{r}} = \mathbf{r}/\,\|\mathbf{r}\|$) and $\mathbf{u}_i, i = 0, \ldots, L$ are calculated. These inner product coefficients, $y_i = \langle \tilde{\mathbf{r}}, \mathbf{u}_i \rangle$, form the received signal point $\mathbf{y} = [y_1, \cdots, y_L]$ in $\mathcal{S}$. Equation (8) describes the operation of the minimum distance detector where it calculates the distances from the received signal point $\mathbf{y}$ to each of the signal points $\mathbf{s}_j$, $j = 1, \ldots, 2^b$ in $\mathcal{C}$ and chooses the closest signal point to be the estimate $\hat{\mathbf{s}}$ of the received signal point. Since each signal point $\mathbf{s}_k$ is associated with a unique $\mathbf{h}_k$, $\hat{\mathbf{s}}$ provides an estimate $\hat{\mathbf{h}}$ to what the received tag signature is.

$$\hat{\mathbf{s}} \ = \ \arg \left(\min_{\mathbf{s}_j \in\, \mathcal{C}} \left\{ \|\mathbf{y} - \mathbf{s}_j\|^2 \right\} \right) \tag{8}$$

III. Design of Prototype 3-bit chipless RFID tag

This section details the design and fabrication of the 3-bit chipless RFID tag. Due to the ease of design, a spiral resonator based tag [4]–[6] was used. The tag essentially consists of two monopole antennas and a spiral filter. A low number of bits was considered for the ease of conducting a comprehensive and thorough analysis.

A. Co-planar Spiral Filter design

The spiral filter design was based on co-planar waveguide (CPW) theory. It consists of 3 spiral resonators where each spiral resonates at a distinct frequency and works as a notch

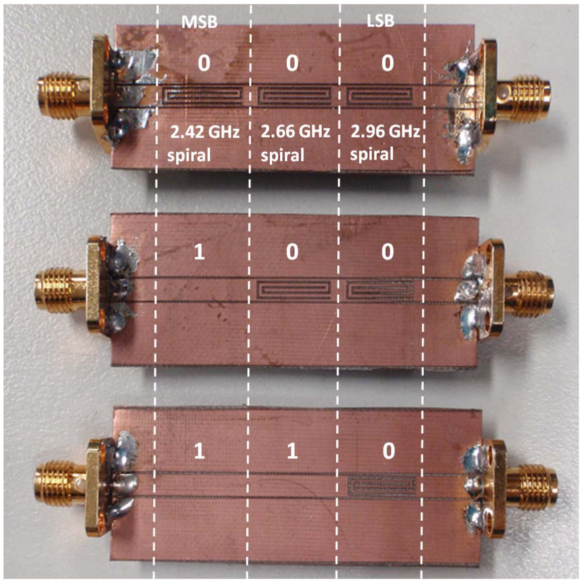


Fig. 2. Spiral resonator based filters carrying data 000, 100 and 110. Each filter has dimensions 2 cm x 5 cm and is fabricated on substrate Taconic TLX-0.

filter at the resonance. By controlling the absence and presence of spirals the frequency characteristics of the filter can be changed, where a resonance is used to encode a data bit '0' and its absence encodes a data bit '1'. Fig. 2 shows three different CPW filters used for encoding data '000', '100' and '110'. The data '110' is encoded using the presence of one spiral resonator while '000' is encoded using all three spirals resonators. The filters were designed and simulated using the software "Computer Simulation Technology (CST) Microwave Studio". Practical measurements obtained using a vector network analyzer (Agilent PNA E8361A) revealed that the resonances occurred centered around 2.42, 2.66 and 2.96 GHz. Here, the lowest and the highest resonance frequencies corresponds to the most significant bit (MSB) and the least significant bit (LSB) respectively.

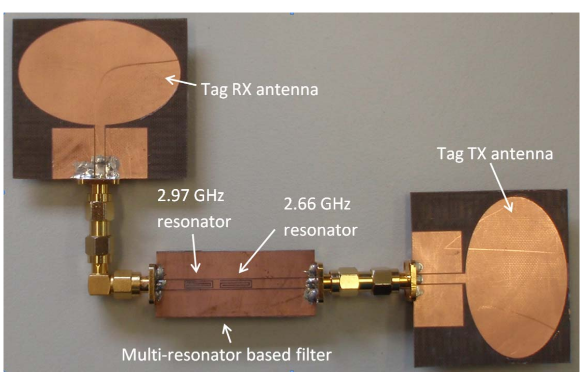
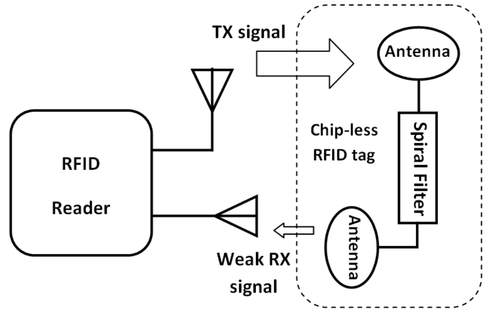
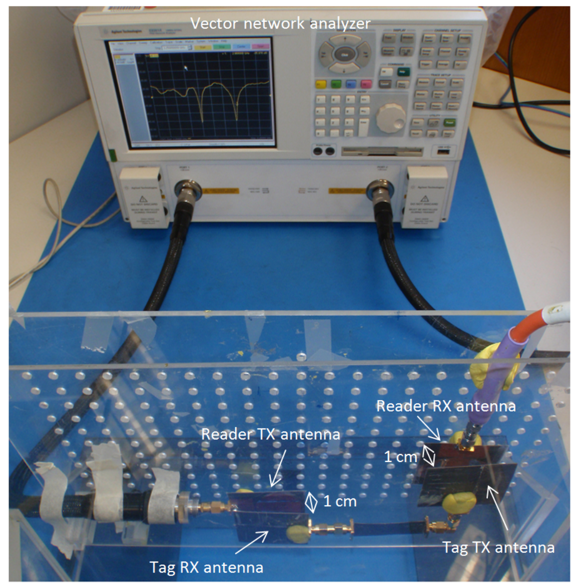


Fig. 3. Complete tag constructed using two monopole antennas and a spiral filter



(a)



(b)

Fig. 4. (a) Chipless RFID System (b) Experiment setup used for acquiring measurements from tags using network analyzer (Agilent PNA E8361A).

B. Monopole antennae & complete tag

Two elliptical CPW monopole antennas [18] were designed that operate from 2.2 GHz to 6.5 GHz. These antennas are then connected to the filter as shown in Fig. 3 where the two antennas are oriented perpendicularly to produce an orthogonal polarization between them. The orthogonality in polarization will aid in reducing interference between the transmitted RFID reader signal picked up by one antenna and the weak reradiated tag signal from the other antenna.

C. Operation of the chipless RFID tag

Fig 4 (a) illustrates the operation of the chipless RFID system. Here, the RFID reader unit transmits an interrogation signal which is picked up by one antenna of the tag which is in turn directed along the filter and transmitted back via the other antenna of the tag. The transmitted weak signal is picked up by the RFID reader unit where it will be analyzed to extract the data carried in the tag.

The experimental setup used in obtaining measurements from the chipless tags is shown in Fig. 4 (b). Here the vector network analyzer transmits a broadband signal (2 - 3.5 GHz) and measures the received and reflected signal power to calculate the scatter parameters (S_{11}, S_{12}, S_{21} and S_{22}) for the two port network formed by the RFID reader transmit and receiving antennas. The measurement of interest is the magnitude and phase of S_{21} parameter (transmission parameter) against frequency, which serves as the channel transfer function between the reader antennas. This transfer function is unique to each tag hence it is interpreted as the frequency signature of the chipless RFID tag.

IV. Results

All 2^3 possible filters were fabricated and the corresponding filter frequency signatures were measured experimentally. Fig. 5 shows the measured frequency signatures (magnitude of the S_{21} parameter) of all the fabricated filters. From these results it was observed that the 3 dB bandwidth of a resonance is about $150 - 200$ MHz. The resonance frequencies that signify each data bit (2.42, 2.66, and 2.96 GHz) vary from filter to filter and has a tolerance of ± 50 MHz due to inconsistencies in the fabrication process.

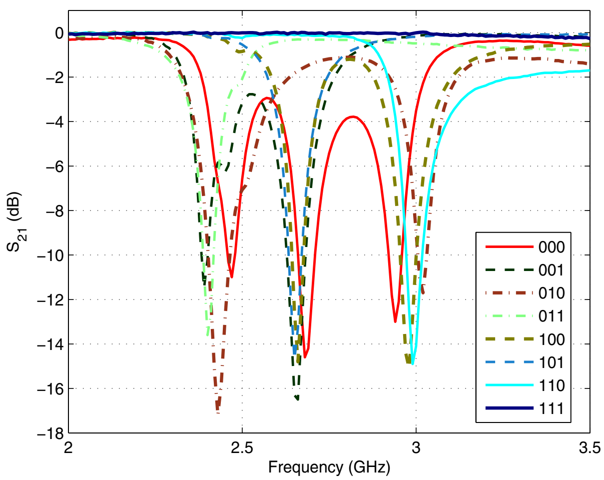


Fig. 5. Measured magnitude of S_{21} vs frequency for all fabricated spiral filters.

Fig. 6 shows the '100' data carrying filter frequency signature and the signatures of the corresponding tag at 1 and 2 cm distances from the reader antennas. From Fig. 6 it is clear that as the distance from the reader antennas increases the received signal level drops due to path loss and also the frequency signature of the tag deteriorates. The tag signature measured at a distance of 1 cm retains most of the spectral characteristics of the filter, however as the distance increases the third resonance shifts from 2.98 to 3.07 GHz.

The tag filter frequency signature (tag without antennae) can be considered a reference signature at zero distance from the reader antennas. Therefore, the filter signatures were used as the reference $\mathbf{h}_k$'s in calculating the set of basis functions discussed in Section II. Table I gives the singular values resulting from performing singular value

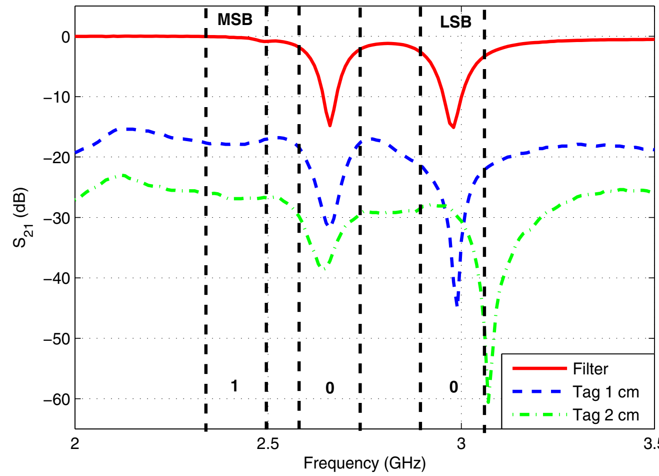


Fig. 6. Signatures of the 100 data carrying spiral filter and corresponding tag at distance 1 and 2 cm from reader antennae

TABLE I
Singular Values σ_i

σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	σ_7	σ_8
2.78	0.32	0.28	0.23	0.13	0.07	0.03	0.02

decomposition on the measured normalized filter frequency signatures as shown in (2). From simulations it was observed that the first four basis functions, $\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3$ and $\mathbf{u}_4$, were sufficient to adequately describe any signature as expressed in (6). Table II lists the coefficients $c_i = \langle \mathbf{h}_k, \mathbf{u}_i \rangle$ or the amounts of each basis function in each filter signature. It is observed from the table that the first basis function is almost the same for all signatures and hence contributes very little information. Therefore, the basis functions 2, 3 and 4 are sufficient to uniquely identify each frequency signature. Hence, using the basis functions, $\mathbf{u}_2$, $\mathbf{u}_3$ and $\mathbf{u}_4$, a signal space was constructed where all 8 frequency signatures, i.e. $000, 001, 010, \ldots, 111$ were plotted as signal points in it as shown in Fig. 7. These 8 signal points can be considered a *constellation* against which measured unknown tag signatures will be matched in order to extract their data.

The measured tag signatures of the '100' tag shown in

TABLE II
Basis Coefficients $c_i = \langle \mathbf{h}_k, \mathbf{u}_i \rangle$

	c_1	c_2	c_3	c_4
Filter 000	0.98	0.13	-0.09	-0.11
Filter 001	0.98	0.16	0.06	0.04
Filter 010	0.98	-0.03	0.11	-0.14
Filter 011	0.99	-0.02	0.15	0.03
Filter 100	0.99	-0.03	-0.16	-0.01
Filter 101	0.99	0.06	-0.05	0.11
Filter 110	0.98	-0.21	-0.05	-0.01
Filter 111	0.99	-0.07	0.03	0.09

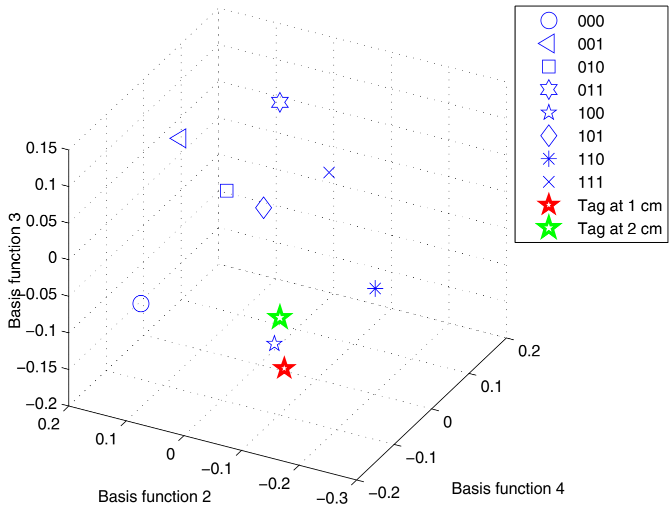


Fig. 7. Signal space representation of frequency signatures

Fig. 6 were also plotted in the signal space shown in Fig. 7. As expected the signal points corresponding to the tag signatures are closer to the '100' constellation point; the minimum distance using (8) was achieved with the '100' constellation point.

V. Conclusion

A novel method to detect encoded data in the frequency signatures of chipless RFID tags has been introduced. Tag frequency signatures are defined using a set of L orthonormal basis functions where all possible data encoding tag frequency signatures are represented as signal points in an L dimensional signal space. The new approach was tested using spiral resonator based chipless RFID tags. Experimental results show that the new approach is able to detect encoded information bits in the frequency signatures of chipless tags. Currently, the noise sources affecting the tag signature are being statistically modeled. This will enable the development of efficient detection algorithms based on the presented mathematical model.

VI. Acknowledgement

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