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Enhanced chipless RFID with Van-Atta and Quantile regression

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Abstract

In this work a chipless RFID tag based on a surface wave impedance (SIW) and a Van-Atta array is presented and assessed. The Van-Atta array it is aimed to reflect the impinging electromagnetic wave on every angle of incidence. The information is encoded in a the compact set of SIW resonators. To improve the detection capabilities and improve the signal to noise ratio, a quantile regression method to enhance the system performance has been considered. A tag prototype has been designed, fabricated, and experimental assessed. The obtained results are quite promising and they demonstrate the potentialities of the proposed chipless tag.

1 Introduction

Modern technology has accommodated various RF components, and the innovative component design [1]. These new designs are cheaper and very practical to use. Thanks to Microtechnology and Nanotechnology's recent progress, offers a more effective and enhanced method to create highly accurate RF component, microwave systems, and sensors that can operate reliably in a wide range of conditions and frequency bands[2]. Modern devices are more effectively conveying signals at microwave frequencies using planar transmission lines, which are preferred in Microwave Monolithic Integrated Circuits (MMIC) [3]. Microstrip line (MSL) passive structures can facilitate such integration since they are economical, compact, light, and extremely versatile. Microstrip structures are particularly suitable for the design of almost all passive microwave devices [3] such as filters, and Radio Frequency Identifier (RFID) [4]. RFIDs have a lots of interesting practical applications such as biomedical, industrial, and commercial. In biomedical, smart sensors systems can measure typical physiological parameters such as Body temperature, Heart rate, Respiratory rate, Blood pressure, Gait analysis, spinal posture, Sweat rate, Parkinson's Disease, Stress Monitoring, Arm and limb motion. Different type of techniques and systems have been developed to deal with the particular situation [5]. Wearable sensors fit with most of the conditions when individual patient monitoring is required. In industrial areas, the RFID sensors have a lots of applications such as item tracking, supply management, logistic, environmental measurement, etc. However, the main drawbck of these low-cost tags' is their limited operative range and the weakness to background noise. Recent research shows that many researchers are working on operating range improvement and post processing method of the chipless RFID tag. Different methods have been presented in [6] to improve the detection and identification of the tags. Usually the information of chipless tags RFID is based on a set of microstrip spiral resonators. Spiral resonators are compact, cheap , and show higher performance than the traditional barcode. The main drawback of spiral resonators is their low-quality factor Q, which limits the resonance and operating range of the device. In this work, a substrate impedance waveguide (SIW) resonator combined with a Van-Atta array has been designed. The SIW will integrate the advantages of the planar design of microstrip structure and non-planar design of the waveguide. The chipless RFID tag comprises a four element Van-Atta array design and a set of SIW resonators to encode the information. Moreover, in this paper, we have also presented the post processing technique called Quantile regression to improve the detection of a chipless RFID tag information in a realistic noisy scenario. The quantile regression is part of the machine learning method. Compare to other machine learning models, the presented quantile regression model quantiles the conditional distribution of responses and expressed them as a function of an independent variable. The quantile regression finds out the influence of independent variable(s) on a response variable in range variation and conditional distribution. The quantile regression can provide detailed distribution characteristics, and complete statistical analysis [8]. Besides, quantile regression is robust to outliers in practical scenarios. The prototype's fabricated design has been assessed, and the preliminary results are auspicious in the potentiality of the proposed method.

2 Mathematical Formulation

In this section, the mathematical formulation has been explained in detail to design the Van-Atta array and the SIW resonators for information encoding.

2.1 Van-Atta array

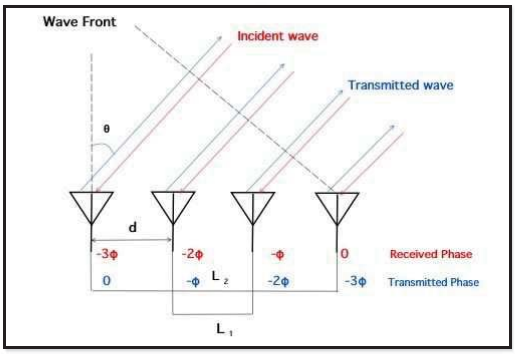

Figure 1. Basic structure of 4 element Van-Atta retrodirective array.

Van-Atta array has many applications in satellite communication, wideband antenna, wireless power transfer system, collision avoidance systems, and many other interesting applications. The four-element Van-Atta array structure is shown in Fig.1. It is composed by passive antenna elements, connected together by transmission lines of suitable length in order to guarantee the correct phase shift. In particular the antenna elements are connected symmetrically to the array centre. The incident field received by each antenna element feeds to the corresponding antenna on the other side an it is radiated back. In Fig.1 feed structure arranged in such a way that the phase distribution of the re-radiated fields is inverse of the received fields. Therefore, the electromagnetic wave re-radiated back towards the incident wave direction. Due to this characteristic, the Van-Atta design is particularly suitable for the passive RFID tags, since they must reflect back the impinging electromagnetic waves with the information. The angle of incidence to respective antenna element is represented as θ in Fig.1.

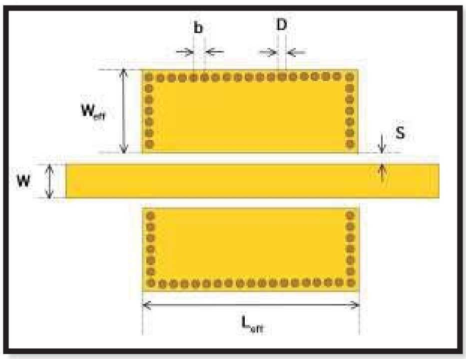

Figure 2. Schematic of a SIW resonator feeded with a microstrip.

2.2 SIW Resonator

SIW cavities are usually used to improve the antenna performances, specifically the return loss of S_{11}. Fig. 2 reports a SIW cavity consisting of sixty two metallized holes of diameter D, the inter-element hole space is b. The combination of these metallic holes can work as a sort of planar waveguide, resonant cavity or transmission line. The simplicity of the design structure provides reduced cost and miniaturization of an antenna. This advantage makes the SIW device most suitable for mass production. In Fig.2, SIW resonators are dielectric structure of top and bottom layer consisting metal. The metal layer walls are realized with circular vias of given diameter D aligned with distance b. The rectangular design of the SIW resonator fed with a microstrip patch is shown in Fig.2. The resonance frequency of the SIW cavity can be calculated using the following relation:

$$f_{TE_{m0q}} = \frac{C_0}{2\sqrt{\varepsilon_r}} \sqrt{\left(\frac{m}{W_{eff}}\right)^2 + \left(\frac{q}{L_{eff}}\right)^2} \tag{1}$$

where ε_r is the dielectric permittivity of the considered dielectric substrate and C_0 is the ligth velocity, m and q represent the two indexes of the transverse electric propagation mode.

$$L_{eff} = ((N-1)\,b + D) - \frac{D^2}{0.95b} \tag{2}$$

$$W_{eff} = W - \frac{D^2}{0.95b} \tag{3}$$

where b is the distance between vias centres, D is the vias diameter, and N is the via number, the term $((N-1)\,b+D)$ represent the length of the SIW cavity. In the considered structure, the SIW resonator is directly excited by the UWB antenna structure; therefore, empirical tuning of D, b, and W parameters is mandatory.

2.3 Quantile Regression

The quantile regression technique is particular suitable to predict the frequency shift and amplitude variations of the resonator response signal, which encode the data. In particular, the encoded data is denoted as the insertion loss y signal. The y signal behavior changes at a particular frequency when the signal gives a phase jumps, which is recorded as pick, also represented as the encoded bit value. In the post-processing part, the signal's phase is recovered and decoded the data bits from the signal retrieved through the quantile regression model described as follows.

In post-processing, the received signal at the reader can be denoted as $y(m), m \in 1,2,...,M$, and $\beta(m)$, $m \in 1,2,...,M$, can be resonance frequency at which resonators performs, where $M \varepsilon \mathbb{N}$ shows the total number of samples. The signal y detected at the Rx antenna signal does not follow any particular distribution form. So, to detect the peak, we have applied quantile regression on the given data as post-processing. As explained before, the quantile regression method convenient when the distribution of the signals is unknown. Theoretically, the quantiles of a random variable are implicitly specified by its probability values. The observed probability values calculate the weight function, commonly gives the quantile of the given data [9].

$$\hat{\mu} = argmin_{\mu\ \varepsilon\ \mathbb{R}} \sum_{m=1}^{M} (y(m) - \mu)^2 \tag{4}$$

$$f(\beta_m/Pr(y(m))) = \begin{cases} 0 & ; \quad Pr \geq \hat{\mu}, \\ Pr & ; \quad Pr < \hat{\mu}. \end{cases} \quad \forall\, m = 1,\ldots,M\ \varepsilon\ \mathbb{N} \tag{5}$$

As per the model in [9], the mean $\mu(y(m))$,unconditional mean $\hat{\mu}(y(m))\ \forall\ m \in 1,2,\ldots,M$, and the variance $\sigma(y(m))$ of the signal y is calculated. The knowledge of mean value $\mu(y(m))$ gives the unconditional mean $\hat{\mu}$ and probability $Pr(y)$ of the signal y at a sample of the signal y. Eq.(4) represents the unconditional mean for given $\{m = 1,2,\ldots,M\}$ and provides the mean value at a particular sample $\{m = 1,2,\ldots,M\}$ of signal y. The following Eq.(5) estimates the weight of the function using the unconditional mean $\hat{\mu}$ and the probability Pr of the signal $y(m)$. However, the above mathematical model only works during an ideal condition when no noise is present. For the practical scenario we have updated the weight function to perform in noisy environment. The updated weight function Eq. (6) finds the location of the peak within the frequency range even in the case of frequency shift. The advantage of this function is that this function calculate the quantile for the conditional mean value for a given frequency step size $[\beta_{min}, \beta_{max}]$ instead of calculating a quantile of the whole signal $y(m)$. Where β_{min} and β_{max} are the lower and the higher frequency value of the signal y. The bandwidth is calculated by $BW = \beta_{min} - \beta_{max}$ of the given signal y, also represents the frequency range of the signal y.

$$f(\beta_m/y(m)) = \begin{cases} 0 & ; \quad y(m) \geq \hat{\mu}, \\ y(m) & ; \quad y(m) < \hat{\mu}. \end{cases} \tag{6}$$

Where, $\forall\ m = 1,\ldots,M \in \mathbb{N}\ and\ \forall \in [\beta_{min} : \beta_{max}]$

$$\beta_{min} = \beta + j * d\delta(n)\ ,\ \ d\delta(n) \in [0:1],\ j \in \mathbb{N} \tag{7}$$

$$\beta_{max} = \beta_{min} + d\delta(n)\ ,\ d\delta \in [0:1] \tag{8}$$

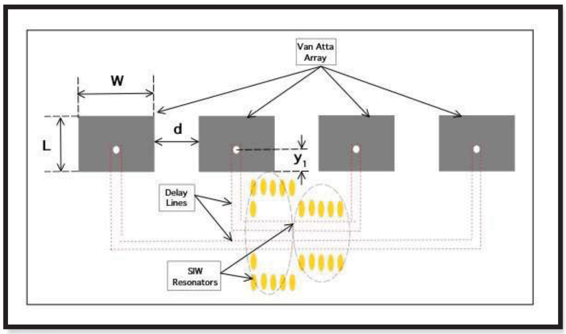

Figure 3. Schematic of the designed chipless RFID prototype tag.

3 RFID Tag Description and Experimental Results

The schema of the proposed prototype is shown in Fig.3. The four elements of the Van-Atta array is designed in a rectangular patch fed with microstrip line. The rectangular patch corners are truncated to achieve circular polarization. The antenna array is fabricated with a ceramic dielectric substrate, ARLON25N. The ARLON25N design parameters are $\varepsilon_r = 3.28$ thickness $t = 0.8mm$, $tan(\delta) = 0.001$. The designed prototype antenna array operates at $2 - 3.2GHz$ with a bandwidth of about $100MHz$. The prototype antenna dimensions of are $W_a = 10mm$, $L_a = 7.8mm$. The feeding point is designed to provide an antenna impedance of $Z_a = 50\Omega$. The array element line are connected at $W = 1.7mm$. The information has been added through the reflected electromagnetic wave, a group of SIW resonators has been added to the array lines connected as symmetrical Van-Atta antenna elements, as reported in Fig.3. The experimental results show the prototype with four bits encoded in the SIW resonator. However, it is important to note that the more SIW resonator can increase the bit number. The experimental has been done using a signal generator with a power $P_{tx} = 100mW$, an horn antenna with a gain $G_{tx} = 17dBi$ and a circulator, it is a typical mono-static reader. A low-cost USB spectrum analyzer analyzes the received signal to demodulate, visualize, and store the information. The prototype has been assessed considering different tag configurations. Fig. 5 report the experimental data obtained with the tag configuration of 11110. The last resonator has been short-circuited using a small copper tape. The data reported in Fig. 5 shows that the peaks encoded as "1" are correctly detected despite the noise level and amplitude level difference of the first two resonators concerning the others. The experimental results are presented only for a selected set of encoded bits. However, the completeness of experiments with different tag configurations has been carried out. The five resonators with resistive load (soldering surface mount device SMD components) also, in this case, the number of tag configurations has been extended from 2^5 to 200. The last experiment results show the limitations of the quantile regressor. Problems come when the peaks depth are flustered too much. A typical situation is reported in Fig. 6. Fig.6 shows the signal retrieved at the tag with all five resonators activated (tag configuration 11111) as it can be seen that with quantile regressor, only the last three peaks are identified correctly Fig. 6. The first two resonances have not been correctly identified. This happens due to the high difference between the peaks depth and the peaks amplitude difference, and the resonances are greater than $10dB$. The real-time scenario reported in Fig. 6 presents a depth difference of about 11 dB between the first two resonances, located at 2.2 and $2.5GHz$ frequency range, and the last peak at 3.0 and $3.1GHz$ frequency. This situation occurs only when the resonators present much difference in the quality factor. Moreover, in the last experiment, a high peak perturbation has been deliberately introduced by a resistive load $R_s = 1500\Omega$ on the last resonator, which assesses the robustness of the Quantile regressor and demonstrate its potential in detection technique.

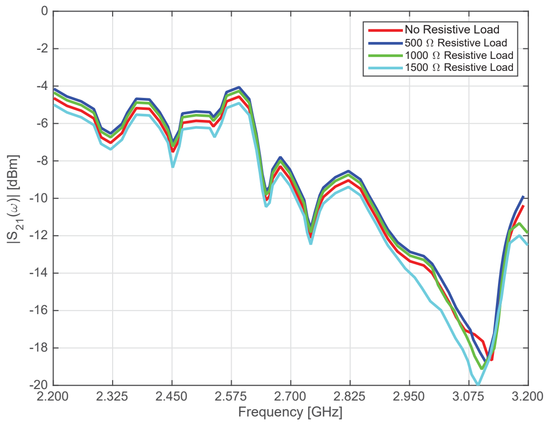

Figure 4. The effects of resistive loads on the resonator response.

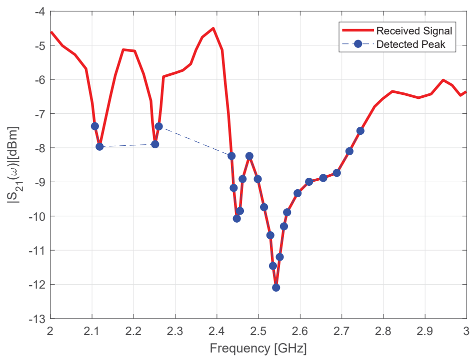

Figure 5. Peak detection for the received real-time signal with the tag configuration of 11110 using new proposed method.

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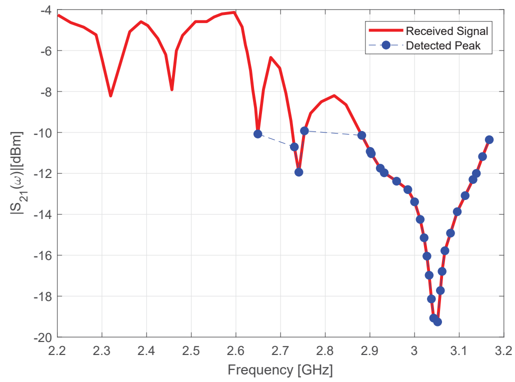

Figure 6. Peak detection for the received real-time signal with the tag configuration of 11111 using new proposed method.

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