Software-defined Reader for Multi-modal RFID Sensing

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***Abstract*—In this work, the feasibility of a system for the detection of multi-modal RFID sensing is presented. A reader is designed for detecting multiple resonances of frequency-shifting RFID sensors, each resonance corresponding to a different sensed variable. The reader exploits information of the actual return loss between the tag antenna and the RFID IC, rather than the tag power-on threshold that has been typically used in the prior art, overcoming limitations associated with the power-on threshold function. The estimator for extracting the return loss of a tag wirelessly is derived and experimentally tested with a low-cost software-defined radio platform. The developed platform can serve both the purposes of a tag performance testing reader and a central processing station for next-generation multi-sensor RFID tags.**

***Index Terms*—RFID, Sensors, Software Defined Radio, Resonance, Detection**

I. Introduction

Radio frequency identification (RFID) tags have been extensively presented in the literature for wireless sensing; RFID is an appealing platform for low-cost, small form-factor, disposable sensors with integrated circuits (ICs) that cost a few cents and antennas that feature a very low profile. Although the primary purpose of typical RFID tags is to backscatter digitally-modulated static information (ID code stored in IC's memory) towards an interrogator/reader, RFID tag designs are often modified to dynamically alter the electromagnetic properties of the antenna based on a sensed quantity; that way the sensor data is "parasitically" modulated on the tag's frequency response rather than in digitally-modulated backscatter. Examples include utilizing dielectric constant-changing substrates that affect the tag's resonance frequency depending on humidity levels [1], strain sensors with antennas whose effective area is stretched when strain is applied and exhibit a resonance frequency shift [2], microfluidic sensors with matching networks that show resonance shifts depending on the permittivity of the tested liquid [3].

The majority of the RFID sensors in literature is focused to monitoring one variable only, relating the variation of the sensed quantity to a shift of the tag's resonance frequency. However, there are scenarios where multiple variables need to be monitored in the same system, e.g. temperature and humidity inside a room. This calls for new sensors that feature multiple resonance frequencies, each coupled with a sensed variable on the same tag (Fig. 1). This work discusses

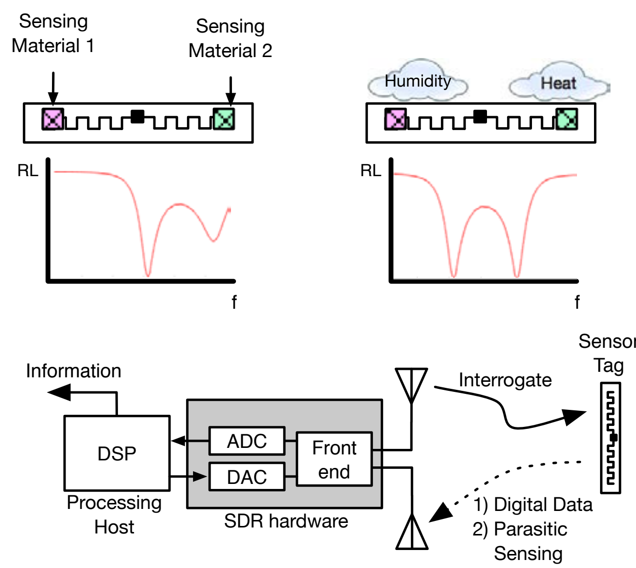

Fig. 1. Multi-modal RFID sensing system. Top: two resonances, each for a different sensed variable. Bottom: Software-defined radio system for interrogation of digital data and "parasitic" sensing data extraction.

techniques to detect multiple tag resonances that will enable *multi-modal* RFID sensing and implementation in modular, low-cost software-defined radio (SDR) platforms.

II. Resonance Detection

In the prior art, a popular form of sensor detection at the reader utilizes the tag power-on threshold, i.e. the minimum power required to power on a tag at a certain frequency. The power-on threshold is given by

$$P_{\text{on,thr}} = \frac{P_{\text{IC,min}}}{G(1-\text{RL})} = L\ P_{\text{tx,thr}} \quad (1)$$

where $P_{\text{IC,min}}$ is the minimum power required to turn on the RFID tag's IC, G is the tag antenna's gain at the direction of interrogation, and RL is the tag antenna-IC return loss

$$\text{RL} = |\Gamma|^2 = \left|\frac{Z_{\text{IC}} - Z_a^*}{Z_{\text{IC}} + Z_a}\right|^2 \quad (2)$$

with Z_{IC} and Z_a being the input impedance of the IC and the antenna, respectively. L is the path loss between the reader and the sensor and $P_{\text{tx,thr}}$ is the minimum output power of the reader that will turn on the tag. The sensed quantity is often related to the frequency point where $P_{\text{on,thr}}$ is minimized. However,

1) $P_{\text{on,thr}}$ minimization is unnecessarily limiting the system to detecting a single resonance only.
2) Typically, the tag antenna is designed in a way that directly relates the sensed quantity with its resonance frequency. However, the RL minimum does not necessarily coincide with the $P_{\text{on,thr}}$ minimum.

The latter happens because a) $P_{\text{on,thr}}$ is not linearly related to RL, and b) the antenna gain G is also frequency-dependent. Moreover, the $P_{\text{on,thr}}$ function tends to "compress" for low values of RL, thus smoothing out resonances and turning sharp frequency regions of good matching to very wide ones.

For 2), a solution could be to relate the sensor variation directly with the $P_{\text{on,thr}}$ resonance instead of RL by predicting $P_{\text{on,thr}}$ with simulated data. However, this would require to a priori generate the $P_{\text{on,thr}}$ function for every possible RL function and form a lookup table (LUT) of discrete resolution.

Instead, both 1) and 2) can be accommodated by using a simple transformation to extract the return loss from the measured $P_{\text{on,thr}}$. This does not require a priori calculation of LUTs and allows to extract the actual antenna resonances and perform multiple peak detection for multi-modal sensors. The return loss function can be extracted with the estimator

$$\widehat{\text{RL}} = 1 - \frac{P_{\text{IC,min}}}{G\ P_{\text{on,thr}}}. \tag{3}$$

In a real environment, the power-on threshold will fluctuate because of fading

$$P_{\text{on,thr (dBm)}} = \bar{P}_{\text{on,thr (dBm)}} + N, \tag{4}$$

where $\bar{P}_{\text{on,thr (dBm)}}$ is the nominal power required to turn on the tag and $N \sim \mathcal{N}(0, \sigma^2)$ is normally distributed with zero mean and variance σ^2. Then, $P_{\text{on,thr (dBm)}} \sim \mathcal{N}(\bar{P}_{\text{on,thr (dBm)}}, \sigma^2)$. In linear scale, $P_{\text{on,thr}} = 10^{P_{\text{on,thr (dBm)}}/10}$ is log-normally distributed $\log\mathcal{N}(\bar{P}_{\text{on,thr (dBm)}}, \sigma^2)$. Then, the mean value of the RL estimate from noisy $P_{\text{on,thr}}$ data is

$$\begin{aligned}\mathbb{E}[\widehat{\text{RL}}] &= 1 - \frac{P_{\text{IC,min}}}{G\ \mathbb{E}[P_{\text{on,thr}}]} \\ &= 1 - \frac{P_{\text{IC,min}}}{G\ \bar{P}_{\text{on,thr}}} \exp\left\{\frac{\ln(10)\ \sigma^2}{20}\right\} \neq \text{RL},\end{aligned} \tag{5}$$

thus the estimate is biased (distorted) because of the power fluctuation. The unbiased estimator is

$$\widehat{\text{RL}}_{\text{ub}} = 1 - \frac{P_{\text{IC,min}}}{G\ P_{\text{on,thr}}} \exp\left\{-\frac{\ln(10)\ \sigma^2}{20}\right\}, \tag{6}$$

which can be applied to averaged $P_{\text{on,thr}}$ measurements to extract RL. It is easy to note that

$$\mathbb{E}[\widehat{\text{RL}}_{\text{ub}}] = \text{RL}. \tag{7}$$

Then the resonance frequencies correspond to the minima of the RL function and can be estimated by solving

$$\frac{\partial \widehat{\text{RL}}_{\text{ub}}}{\partial f} = 0. \tag{8}$$

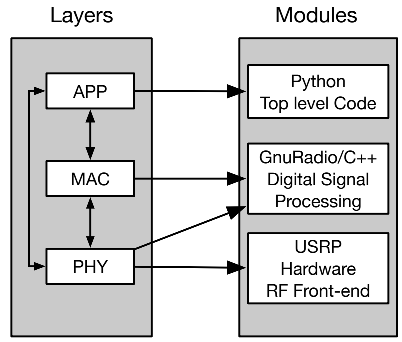

Fig. 2. Frequency sweeping RFID reader architecture.

III. Software Defined Radio Implementation

The whole reader functionality is implemented on a SDR platform due to the flexibility to reconfigure both software modules and hardware RF front-ends. It is worth to mention that a commodity SDR costs one order of magnitude less than commercial testing RFID readers and at the same time gives the flexibility of expanding the reader functionality with additional software modules.

The reader is sweeping across a wide frequency band (750 MHz to 1.1 GHz) and determines for each frequency point the minimum transmit power to turn on the RFID tag. The indication that the tag was powered on is the successful decoding of the tag's backscattered electronic product code (EPC) as required by the Gen2 RFID standard. The reader's functionality spans three layers:

- Physical: Interrogation signal generation, Tag backscatter decoding
- Medium Access Control: Gen2 RFID protocol implementation
- Application: Frequency sweeping/Power-on threshold algorithm, RL extraction

A *cross-layer* development is followed where the application layer implementing the algorithm (in python) for determining $P_{\text{on,thr}}$ directly communicates with the physical layer to control the output power and carrier frequency (Fig. 2). The signal processing blocks and MAC protocol are implemented in C++ and are based on the work in [4], where a subset of the Gen2 protocol was implemented for GnuRadio and the USRP SDR platform.

The SDR hardware's Tx power needs to be calibrated to remove the effects of non-linear behavior of its amplifiers for low and high power levels, as well as the variation of the output power due to frequency-selective components, filters, and transmission lines. The required signal attenuation $A_{\text{(dB)}}$ needs to be found for a desired Tx power level $P_{\text{tx (dBm)}}$ at a certain frequency. Then, $A_{\text{(dB)}}$ can be used to precisely control the reader's interrogation power. The Tx power is measured with a power meter for $A_{\text{(dB)}} \in [-40,\ 0]$ dB, to generate a matrix $P_{\text{tx}}[A, f]$. Then, the matrix is inverted to obtain $A[P_{\text{tx}}, f]$. Instead of utilizing a LUT, a 5×5-order polynomial is obtained by surface fitting and a continuous

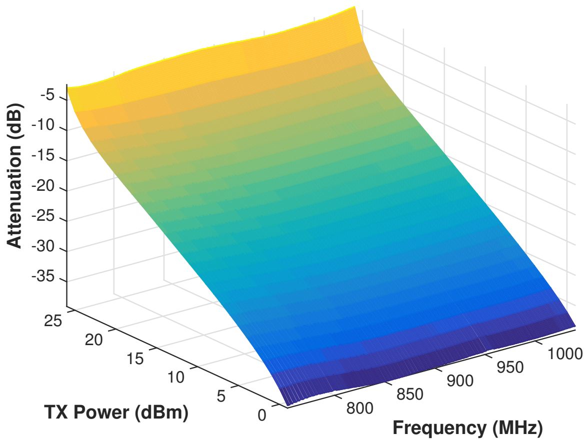

Fig. 3. Required attenuation for each power level and frequency.

Fig. 4. Double resonance inkjet-printed tag for testing.

function $A(P_{\text{tx}}, f)$ is determined to use for power sweeping (Fig. 3).

To calculate the power-on threshold from the Tx power threshold, the reader-to-tag channel response (attenuation, multipath) is required. A calibration tag with known $P_{\text{on,thr}}^{\text{REF}}$ is interrogated by the reader and the minimum Tx power $P_{\text{tx,thr}}^{\text{MEAS}}$ is determined. Then, the estimated reader-to-tag channel is

$$\hat{H} = P_{\text{tx,thr}}^{\text{MEAS}} / P_{\text{on,thr}}^{\text{REF}} \tag{9}$$

and for any measured tag, the power-on threshold is

$$P_{\text{on,thr}} = \hat{H} \ P_{\text{tx,thr}} \tag{10}$$

which is used to extract $\widehat{RL}$ as described in Sec. II. For $\widehat{\text{RL}}_{\text{ub}}$, the fluctuation σ^2 is calculated as the variance of multiple $P_{\text{on,thr}}$ measurements of the reference tag.

IV. Measurements

To test the reader, a wideband RFID tag is designed and inkjet-printed on paper (Fig. 4) with resonances around 800 and 1000 MHz. The power-on threshold is determined with the software-defined reader and is shown in Fig. 5. Utilizing the gain variation across the frequency band in Fig. 6, the RL is extracted and is shown in Fig. 7. There is a variation in the "depth" of the RL around the resonance frequencies, which is a result of the "compression" effect of $P_{\text{on,thr}}$ as described in Sec. II. However, this does not affect the position of the minima, which allows a successful detection of the tag resonances despite the amplitude scaling.

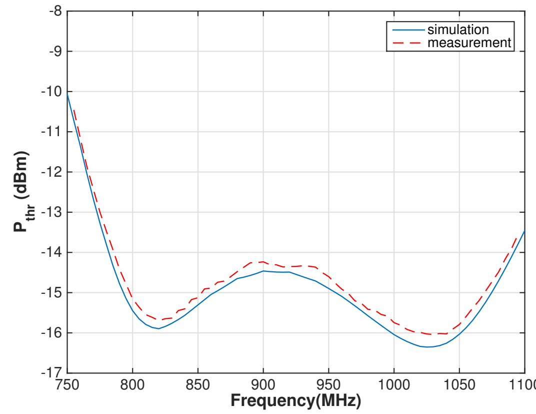

Fig. 5. Simulated and measured Power-on threshold.

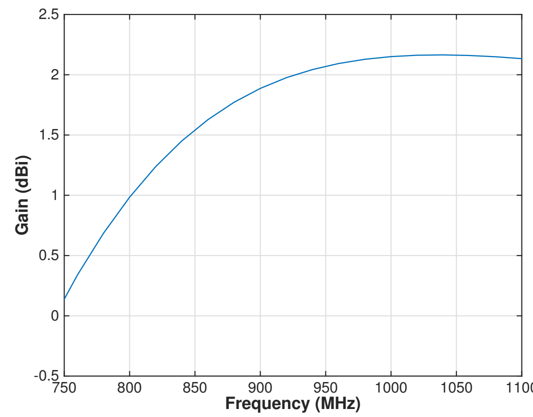

Fig. 6. Tag antenna gain variation with frequency.

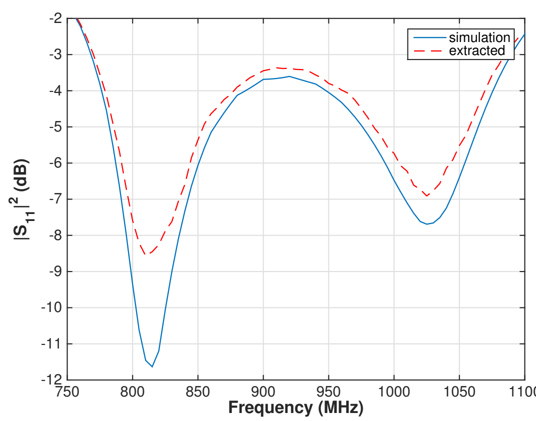

Fig. 7. Simulated and extracted Return Loss.

V. Conclusion

In this work, a low-cost implementation of a platform for multimodal RFID sensing was presented. The steps for extracting the return loss of a tag from its power-on threshold

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were given. The method provides the possibility to detect multiple real RL resonances of a tag which do not necessarily occur at the same frequencies as the P_{on} resonances. The described system can be used both as a "wireless VNA" for wirelessly measuring the RL of the tag antenna-IC system, and as a multimodal sensing platform. The system is scalable to multiple tags with multiple resonances, by mapping each RL response to a tag's ID.

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