A Novel RFID-Enabled Strain Sensor Using the Double Power Measurement Technique

Masoumeh Hasani[1], *Arnaud Vena*[2], *Lauri Sydänheimo*[1], *Leena Ukkonen*[1], *Manos M. Tentzeris*[3].

[1]*Tampere University of Technology, Tampere, Finland*

[2]*University of Montpellier 2, Montpellier, France*

[3]*Georgia Institute of Technology, Atlanta, United States*

***Abstract* — This paper studies a novel RFID-enabled strain sensing approach using the radar cross-section measurement technique and taking advantage of the nonlinearity properties of the RFID chip. As a proof of concept, we applied the method for the measurement of an RFID-enabled strain sensor that was realized on fabric using electro-textiles in order to observe large variations of peak-power frequencies and corresponding strain levels. We carried out the radar measurements first applying the three-target calibration technique and then using the novel double-power-detection method, which relies upon the detection of the backscattered response for two distinct transmitting power levels and then calculating the difference of these two responses. The nonlinearity of the chip causes a large variation of its impedance value and thus a large difference of RCS values for carefully chosen power levels, allowing for the elimination of the need for calibration. Practical measurements have validated the method and the reliability of the technique.**

Index Terms — RFID, embroidered sensors, strain sensors, wireless, RCS, double power, Nonlinear IC.

I. INTRODUCTION

In this paper, a chip based RFID-enabled strain sensor is presented, which can be interrogated using a calibration-free chipless technique. The passive RFID tag is composed of an IC connected to an antenna with a matching circuit. To make an RFID tag sensitive to a physical parameter, the technique is to make either the antenna or the matching circuit's electrical/electromagnetic performance sensitive to the change of the sensed parameter. For some gas or humidity sensors [1], the sensing technique consists of the deposition of a film of a sensitive material with a complex permittivity value varying as a function of the concentration of the physical parameter to detect. For numerous antenna-based strain sensors [7], the electrical length of the antenna changes depending on the strain value [2]. As it has been reported in [3], there are two techniques to detect these types of sensors. The first technique utilizes the read range extraction that relies on the detection of the threshold power (minimum reader transmitted power to activate the RFID chip). In the second technique, sensing is based on the measurement of the tag RCS, that is mostly used for identification of chipless tags.

Based on the results published in [3], the advantages of utilizing a radar cross section (RCS)-based technique are the simplicity and the lack of the need for specific protocols for the detection of the sensed parameters. However, the detection of the sensor outside the anechoic chamber, especially in highly-cluttered indoor environments, requires an accurate calibration process to remove all static reflections from the ambient scatterers [5]. This makes the detection process quite time-consuming and complex.

The novel detection method introduced in this work cancels the effect of environmental reflections taking advantage of the nonlinear properties of the chip impedance. Transmitting two distinct power levels (e.g., -5 dBm and 14dBm) toward the tag sensor, which can guarantee a large variation of the chip impedance value, causes very different EM (RCS) responses of the tag. Contrary to the chips typically used in the RFID tags, ambient scatterers feature a linear behavior for the considered transmitted power range (<27dBm). Thus, the normalized response of the background reflections does not vary as a function of the power. Thus, when subtracting the distinct EM responses of the tag for the two power levels measured in a real environment, we could potentially remove the effect of the background almost completely and keep only the tag's response. Fig. 1 shows the principle of this novel

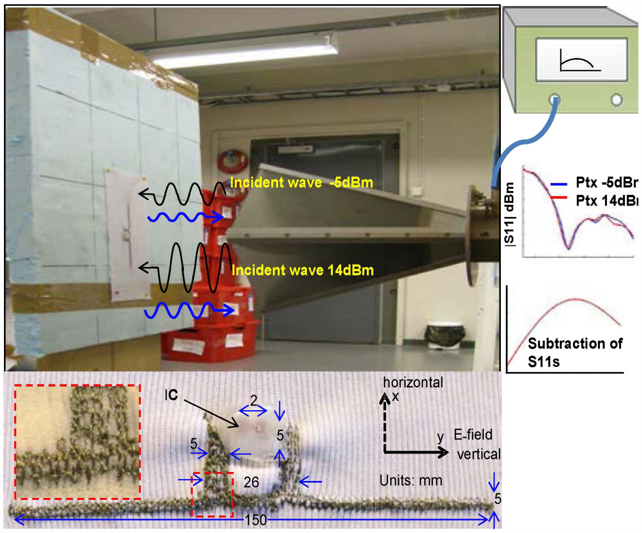

Fig. 1. Principle of the strain sensor interrogation using dual-power measurements.

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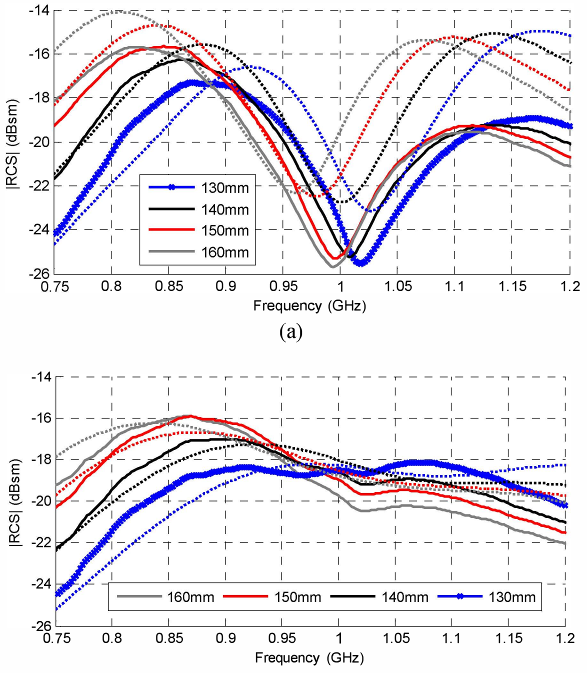
method for a proof-of-concept strain sensor.

II. PASSIVE SEWN SENSOR DESIGN

The proposed detection method has been validated by implementing a strain sensor for which a large variation of the peak-RCS frequency can be observed when subject to a pulling force. This sensor has been fabricated with the embroidery technology on a stretchable fabric in a similar way to [3]. The presented technology could potentially enable the easy implementation of large "smart skins" as well as of large textile surfaces covered by numerous strains sensors to sense crack or deformations on civilian buildings, such as monuments and bridges.

Simulation of Sensor Tag

The sewn strain sensing tag that is shown in Fig. 1 has been simulated using CST Microwave Studio. By using the ideas reported in [4], this design has been optimized based on the electrical parameters of the fabric substrate and the conductive loss of silver threads. The stretchable fabric is modeled as a substrate with the thickness of 1 mm, $\varepsilon_r = 1.4$ and $\mathrm{Tan}\delta = 0.022$ at 1 GHz [3]. When the tag is stretched longitudinally outwards, the antenna's electrical length increases and its resonant frequency decrease [3]. To accurately quantify the effect of this electrical length variation, the RCS of the tag corresponding to a normally incident plane wave has been simulated. For simulation, the chip (NXP UCODE G2iL SL3S1203AC0) has been modeled with a parallel combination of R_{IC} and C_{IC}. To get a good agreement between simulation and measurement results, for the data near the peak-RCS frequency, $R_{IC} = 8.5\ \mathrm{K\Omega}, C_{IC} = 0.9\ \mathrm{pF}$ and, $R_{IC} = 500\ \Omega, C_{IC} = 1.09\mathrm{pF}$ are extracted, respectively, for the transmitted power of -5 and 14 dBm. The minimum and maximum reader transmitted power levels (-5 and 14 dBm) have been selected for sake of proof of concept, respectively, according to the minimum required power that is sufficient to turn on the tag and detect the reflected signal from the tag, and to the power limitations of measurement system. The dashed lines in Fig. 2 (a), (b) show the simulated RCS for two different transmitted power levels and 4 different antenna lengths.



(a)

(b)

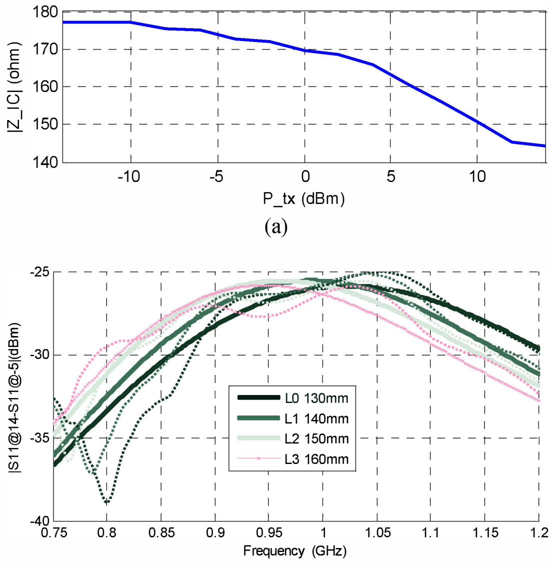
Fig. 2. Four different antenna lengths have been simulated and measured. (a) The dashed lines show the simulated RCS and the solid lines shows the measured RCS for transmitted power -5 dBm. (b) The dashed lines show the simulated RCS and the solid lines shows the measured RCS for transmitted power of 14 dBm.

In the simulation results for both power levels the effect of the change of the length of the antenna on the RCS magnitude and frequency variation can be clearly detected. The RCS magnitude shifts from -16.8 dBsm to -14 dBsm and from -18.7 dBsm to -16.3 dBsm, respectively, for -5 dBm and 14 dBm transmitted power. Moreover, the frequency shifts of 130 MHz and 100 MHz, respectively, for transmitted powers of -5dBm and 14 dBm are clearly visible for the peak-RCS frequency.

III. MEASUREMENT RESULTS

A. Detection of the Sensor Using RCS Measurement

The performance of the sewn sensor was experimentally characterized using the mono-static radar technique with a vector network analyzer (VNA) connected to a horn antenna



(a)

(b)

Fig. 3. (a) The absolute value of chip impedance as function of transmitted power at 915 MHz. (b) The subtraction of measured S11 at -5dBm and 14 dBm for 4 different lengths of tag sensor.

(Fig. 1). As it is explained in detail in [3], the sensor tag is placed on top of a Styrofoam spacer and simple pins have been used to stretch the fabric, subsequently modifying its length. The RCS variation of the strain sensor has been measured using a frequency domain measurement setup for the power levels -5, 14 dBm delivered by the VNA in vertical polarization (Fig. 1). The measurement distance has been optimized for 20 cm, based on the power levels and also to speed-up the measurement. About 1 m read range can be achieved in case of the reader transmitting the maximum allowed power (EIRP). As it is explained in [3] section III part B, the effect of unknown objects around the measurement environment have to be removed by applying calibration which requires additional measurements. Solid lines in Fig. 2 (a), (b) show the RCS values of antenna which has been extracted utilizing equation (2) reported in [3]. As it can be easily seen, the simulation and measurement results (Fig. 2) are quite similar and the absolute value of RCS are increases and the frequency peak decreases with the length of the antenna. This verifies that the applied strain on the antenna can be effectively sensed, monitoring the RCS variation in spectrum and value.

B. Detection of the Sensor Using Double-Power Measurements

The detection of the tag by measuring the return loss S11 and the subsequent extraction of RCS typically requires complex post-processing calculations and additional calibration measurements [3]. Using the proposed method, the measurement setup is similar to the one explained in the previous section. The return loss S11 of the sensor tag for different lengths has been measured once for transmitted power -5 dBm and then for 14 dBm. In this case, no additional background/calibration measurements are needed since the "clutterless" detection of the sensed parameter is achieved by subtraction of the scattering parameters of two different power levels.

By correlation between measurement and simulation results, the impedance of the chip for the measured tag prototype as function of transmitted power is plotted in Fig. 3.(a). Because of the nonlinear properties of the RFID chip, its impedance varies significantly for different power levels incident to the tag. The backscattered signal of the sensor tag for each power level always includes the static reflections from ambient scatterers. It is possible to remove these reflections by subtraction of the scattered signals and extract the pure tag response. This can be proved using the tag detection system proposed in [6].

Based on the model presented in [6], the total system response including the effect of measurement channels, isolation measurement and ambient scatterers are recorded in block M as follow,

$$M_{total} = I + T \cdot C \cdot R + T \cdot O \cdot R \qquad (1)$$

where the effect of cables and antennas in transmit and receive path are modeled respectively, by block T and R, and the unknown objects and tag in front of reader antenna are modeled respectively, using block O and C. Finally $I = T \cdot D \cdot R$ represents the effect of direct coupling between antennas when neither tag C nor objects O are in front of the antennas. The system response can be considered as function of transmitted power and for different transmitted power P_{tx1} and P_{tx2} is represented in (2), (3).

$$\begin{aligned} M_{total}(\mathrm{P}_{tx1}) = {} & I(\mathrm{P}_{tx1}) + T(\mathrm{P}_{tx1}) \cdot C(\mathrm{P}_{tx1}) \cdot R(\mathrm{P}_{tx1}) \\ & + T(\mathrm{P}_{tx1}) \cdot O(\mathrm{P}_{tx1}) \cdot R(\mathrm{P}_{tx1}) \end{aligned} \qquad (2)$$

$$\begin{aligned} M_{total}(\mathrm{P}_{tx2}) = {} & I(\mathrm{P}_{tx2}) + T(\mathrm{P}_{tx2}) \cdot C(\mathrm{P}_{tx2}) \cdot R(\mathrm{P}_{tx2}) \\ & + T(\mathrm{P}_{tx2}) \cdot O(\mathrm{P}_{tx2}) \cdot R(\mathrm{P}_{tx2}), \end{aligned} \qquad (3)$$

and the subtraction of $M_{total}(\mathrm{P}_{tx1})$ and $M_{total}(\mathrm{P}_{tx2})$ is equal to,

$$\begin{aligned} M_{total}(\mathrm{P}_{tx1}) - M_{total}(\mathrm{P}_{tx2}) = {} & [T(\mathrm{P}_{tx1}) \cdot C(\mathrm{P}_{tx1}) \cdot R(\mathrm{P}_{tx1}) \\ & - T(\mathrm{P}_{tx2}) \cdot C(\mathrm{P}_{tx2}) \cdot R(\mathrm{P}_{tx2})]. \end{aligned} \qquad (4)$$

Since the term of O and I are independent of changing power, thus, in (4), the total measurement results of system are only dependent of the tag responses for two different powers and the effect of unknown objects can be easily removed. Moreover, even if T and R are still present in the equation, we can see a significant variation of the peak-power frequency as function of the strain as shown in Fig. 3 (b). The subtraction of the scattered parameters of two different powers for different applied strains is illustrated in Fig. 3 (b) (the dashed lines). The solid lines show the best fitted curves using the polynomials with the order of 20. As one can see, by increasing the length of the antenna the frequency of the peak are shifted and this verifies that applied strain can be effectively sensed.

IV. CONCLUSION

In this paper, we have presented a novel measurement method for sensing the RFID strain sensor tag, based on the radar measurement technique. This method is able to detect the sensed parameter of fabric-based strain sensor based on the nonlinearity properties of the IC. In the former measurement method, the sensing was based on the measurement of RCS for which a calibration based on three measurements was needed. Using this novel method, the detection of the sensed parameter is done by measuring the tag response for two different power values which are subtracted.

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