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Passive E-Textile UHF RFID based Wireless Strain Sensors with Integrated References

Xiaochen Chen, Leena Ukkonen, *Member IEEE*, and Toni Björninen, *Member IEEE*

***Abstract*—Highly stretchable e-textile antennas enable wireless strain sensing based on passive UHF RFID tags. We present two sensors both based on a two-tag system, where one tag antenna is sensitive and one is insensitive toward strain. This way, we achieve novel referenced strain sensors for unambiguous readout. We outline the antenna system development to achieve high EM isolation between the tags and present results from the wireless testing of the sensor.**

***Index Terms*—Wireless strain sensors, electro-textiles, conductive threads, dipole antennas, antenna coupling, RFID**

I. INTRODUCTION

THE mechanism of modulated scattering utilized in passive radio-frequency identification (RFID) tags enables digital ultra-low-power radio communication over the distance of several meters. This makes the passive RFID-enabled sensor tags a compelling approach to the internet of things (IOT) [1].

Examples of sensor tags include gas [2–3], humidity [4], temperature [5], and strain sensors [6–7]. In all of these works, the sensing mechanism is based on antenna-sensor structures whose EM properties are altered by the monitored environmental parameter. This enables the very low-complexity devices desired in IOT applications. Still, the shortcomings in the current state-of-the-art are the lack of a reference readout and degradation in the sensor readout distance due to antenna detuning caused by alterations in the EM properties of the antenna. Recently, two approaches to remedy this have been investigated: the readout from the backscattered signal strength [7] and establishment of a stable reference state by using a reconfigurable antenna [3]. However, the sensor [7] lacked an embedded reference and in [3] the sensor readout was based on monitoring the detuning of the antenna and the implementation of the switch required for the referenced readout was reserved as future development.

In this work, we present two RFID-enabled strain sensors which provide referenced readouts. The sensors are based on the backscatter readout mechanism presented in [7]. The novel referenced readout is achieved through the EM optimization of a coupled two-tag system where one tag is made sensitive and one insensitive toward strain.

II. SENSOR DEVELOPMENT

The sensor and reference tags are both based on dipole antennas with embedded inductive matching loops as shown in Fig. 1. This is a widely used antenna type in RFID tags [6–7]. The reference tag is made of non-stretchable Copper plated Polyester textile (Less EMF Cat. #A1212) whereas non-stretchable and stretchable (76% Nylon and 24% elastic fiber; Less EMF Cat. #A321) textiles were used in the sensor tag (Fig. 1). Elongation in the stretchable section modifies the EM properties of the tag and enables the sensing functionality. The stretchable and non-stretchable parts were connected using a sewing machine and metal plated sewing thread.

As in [7], the aim was to establish the sensor readout based on the backscatter strength. In an anechoic space, the backscattered power at the reader antenna at distance d from the tags is given by

$$P_{rx} = \frac{1}{4}|\rho_1 - \rho_2|^2 \left(\frac{\lambda}{4\pi d}\right)^4 G^2 G_{read}^2 P_{tx} \tag{1}$$

$$\rho_k = \frac{Z_{ic,k} - Z_a^*}{Z_{ic,k} + Z_a}; k = 1,2, \tag{2}$$

where P_{tx} is the continuous-wave output power of the reader, G and G_{read} are the gains of the tag antenna and reader antenna, respectively, and ρ_1 and ρ_2 denote the antenna-IC power reflection coefficient in the energy harvesting ($Z_{\mathrm{ic},1}$) and modulating ($Z_{\mathrm{ic},2}$) impedance states of the IC, respectively [7]. For simplicity, equations (1–2) assume tag antennas to be co-polarized with a monostatic RFID reader.

Based on (1–2), for effective operation, the sensitivity of the gain of the sensor tag antenna toward strain should be maximized and simultaneous the reference tag's gain should remain approximately constant. Also, both tags should maintain good complex-conjugate-matching with the RFID IC to maximize the sensor readout distance. A fundamental challenge in the sensor optimization is the EM coupling between the antennas in the sensor and the reference tags. This alters their input impedance and radiation properties as compared with isolated antennas. For this reason, a two-antenna system must be considered.

We used ANSYS HFSS (full-wave EM solver based on the finite element method) to model the antenna system. The two different configurations shown in Fig. 1 were found promising in minimizing the coupling. In the final optimization, the geometrical parameters of the antennas were adapted to yield high read range and maximal variation in G^2 of the sensor tag's antenna. The target frequency of the sensor's readout was 866.6

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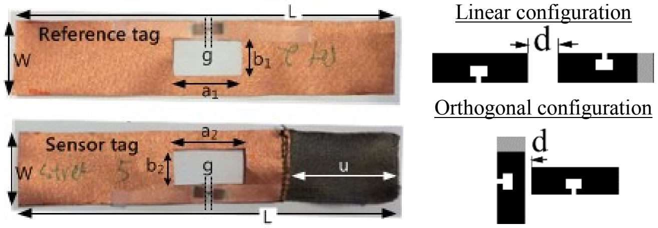


Unit mm	a_1	b_1	a_2	b_2	g	L	W	d	u
Linear	18.7	10	18.6	9.73	2	100	20	20	30
Orthogonal	17.3	10	17.3	10	2	100	20	5	30

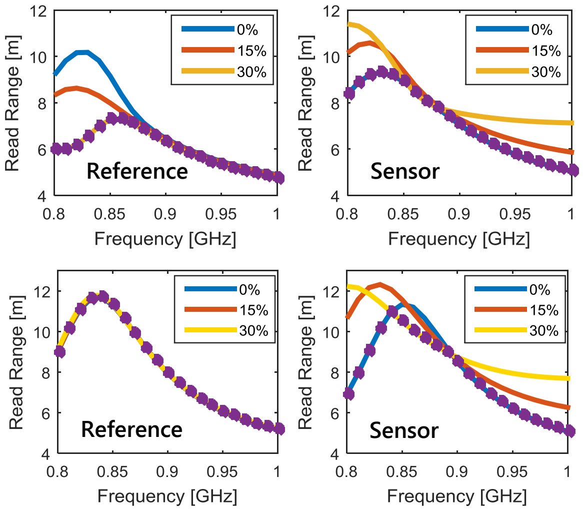
Fig 1. Samples of manufactured tags and studied sensor configurations.

MHz which is the center frequency of UHF RFID band in European countries.

Fig. 2 shows the read ranges of the sensor and reference tags obtained by varying the sensor tags physical length in the HFSS simulation. In contrast to [7], here the read range was obtained by considering the input impedances of coupled antennas instead of isolated ones. As the optimized antennas in Fig. 1 are slightly dissimilar, also the tag read ranges differ even in the absence of strain. In the linear configuration, the read ranges of the sensor and reference tags remained approximately constant at 866.6 MHz with the overall sensor readout distance of 7.2 meters, which is limited by the reference tag. In the orthogonal configuration, the antenna coupling effect is smaller and hence the read range of the reference tag is virtually unaffected by the strain at all frequencies. The antenna elongation changes the read range of the sensor tag, but overall the sensor maintains high read range of 10 meters at 866.6 MHz, which in this configuration is limited by the sensor tag. The G^2 parameter of the reference tag remained almost constant versus strain, as desired, and showed a linear increase for the sensor tag.

III. RESULTS FROM WIRELESS TESTING

In the real application environment, the reference tag enables the compensation of the possible contribution of multipath propagation from the strain readout since the signal from the reader to the closely spaced tags travels approximately through the same channel. In this work we explore the sensor readout based on the percentage variation in the backscattered signal strength of the sensor tag with respect to the references defined as $\Delta P\% = (P_{sns} - P_{ref}) / P_{ref}$, where P_{sns} and P_{ref} are the received signal powers of sensor and the reference tags, respectively.



Fig, 2. Simulated read range of the reference and sensor tags in the linear (top) and orthogonal (bottom) configurations. Markers highlight the minimum read range for all strains up to 30%.

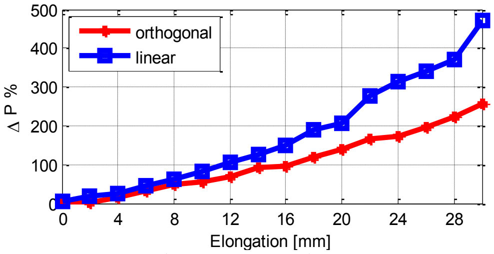


Fig 3. Sensors' measured response to strain.

Measurement of the backscattered power was conducted with the Voyantic Tagformance measurement system. The measurement system and set-up are the same as described in detail in [7]. To avoid colliding responses from the two tags, we addressed the *query* command specifically to the sensor and reference tag IDs. As seen from Fig. 3, $\Delta P\%$ increased monotonically with the strain in both configurations and in the orthogonal configuration the response was highly linear. Thus, the elongation of the sensor tags can be unambiguously associated with $\Delta P\%$. Moreover, the strain increased P_{sns} for both sensors and it remained larger than P_{ref}. Therefore, the strain is not limiting the signal detection at the reader.

IV. CONCLUSION

Stretchable e-textile enables strain-sensitive antennas for passive UHF RFID tags. By including a non-stretchable reference tag and optimizing the two-antenna system we have demonstrated two wireless strain sensors with integrated references. They provide strain readout with regular unmodified RFID reader hardware. Both sensors were attested for strain sensing up 30%. In the orthogonal configuration, the sensor featured a highly linear response, but in comparison with the linear configuration, it occupied a larger area.

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