Low-Cost Inkjet-Printed Fully Passive RFID Tags Using Metamaterial-inspired Antennas for Capacitive Sensing Applications

Sangkil Kim[1], Yoshihiro Kawahara[2], Apostolos Georgiadis[3], Ana Collado[3], and Manos M. Tentzeris[1]

[1]Georgia Institue of Technology, City, GA, 30305, USA
[2]University of Tokyo, Tokyo, 113-8656, Tokyo
[3]Centre Tecnologic de Telecomunicacions de Catalunya (CTTC), Catalunya, Spain

Abstract — A fully passive, compact, and low-cost capacitive wireless RFID-enabled sensing system for capacitive sensing and other Internet of Things applications is proposed. The proposed RFID tag antenna based sensor consists of a closely spaced two-element dipole RFID tag antenna array with a printed capacitive sensor connected to one of the tags. A metamaterial-inspired resonator is used to improve isolation among the two antennas and optimize the size of the antenna structure. When high permittivity materials, such as water or human fingers, are close to the on-tag meander line structure, only one of the RFID chips is able to respond due to the capacitance change, and consequently, detuning of the antenna structure. Therefore the system can distinguish capacitance change using just one fixed operation frequency. All components except from the RFID chips are inkjet-printed on photo-paper using a silver nano-particle ink. The tag dimensions are 84mm x 89mm and the tag is compatible with EPC Class 1 Gen 2 (UHF) standard reader at 915 MHz. Measurements using a commercial RFID reader are used to demonstrate the operation of the fabricated prototype.

Index Terms — Capacitive sensing, RFID, isolation, inkjet-printing, capacitive sensor, remote sensing, meta-material.

I. INTRODUCTION

RFID is a successful solution for the identification of objects in every day applications. However, low cost sensing is the next challenge for the realization of Internet of Things. For instance, RFID could detect *which* coffee cup is in the room but it is impossible to tell *how much* coffee left in the cup. It is also difficult to know *who* touched the cup in the room. Thus the final goal of this work is to extend the capability of standard RFID-based systems to sense the status of the objects and the interaction between a human and objects by focusing on capacitance change near the RFID tag.

Existing sensing systems based on passive RFIDs [1] and wireless power transmission [2] can transmit precise measurement data over a wireless channel by exploiting programmable intelligent low-power microcontrollers. Other systems use separate frequency for sensing and communication [3], or detect capacitance change by the shift of resonant frequency [4]. Antenna based tag sensing is receiving significant attention due to a simple passive architecture, easily adaptable to existing commercial RFID systems [5]. Alternatively, a second tag can be used as a reference to assist in the sensing function [6]. This paper also introduces a sensing technique in which two low-cost RFID chips are utilized in a single tag. In this work however the accuracy of the reference signal is ensured by requiring that the tags are placed closely together in order to enforce the same interrogating signal conditions among them. Sensing functionality is introduced as follows: when the meander line sensing structure on the tag is exposed to lower permittivity materials such as air, both chips are able to respond to the interrogator in turn with unique IDs. When higher permittivity materials such as water and human fingers, are close to the meander line structure, only one of the chips begins to respond due to the capacitance change in the antenna structure. Thus the system can be operated at a fixed frequency, which is a crucial requirement for the efficient use of radio frequency band. This kind of topology can be used for applications such as liquid level detection, and ambient humidity sensing.

However, designing such an intelligent tag is not trivial, as the following challenges have to be addressed: (1) The cross-coupling between the two antennas attached to the two chips on the tag has to be minimized. In addition, the two antennas should be in close proximity so that they are excited by approximately the same interrogating signal and in order to maintain a compact size. (2) The capacitive sensor should be sensitive enough to detect the desired event such as the presence of a human fingertip. Metamaterial structures can be used to enhance the isolation between the two antennas [7], and consequently improve the sensitivity of the sensor.

The rest of the paper is organized as follows. Section II explains the theory and design of the proposed RFID-based sensor. Section III presents experimental measurements including the frequency response and the sensitivity of the proposed sensor, while the last section closes with the conclusions.

II. ANTENNA DESIGN

A meta-material structure consisting of a slot and a series interdigitated capacitor has been introduced in a monopole antenna [7], and was utilized to minimize its size and control the mutual coupling of a two element array. In this work a similar metamaterial structure is introduced in a dipole antenna (Fig. 1). As a first step the size of the interdigitated capacitor is selected in order to achieve a resonance frequency

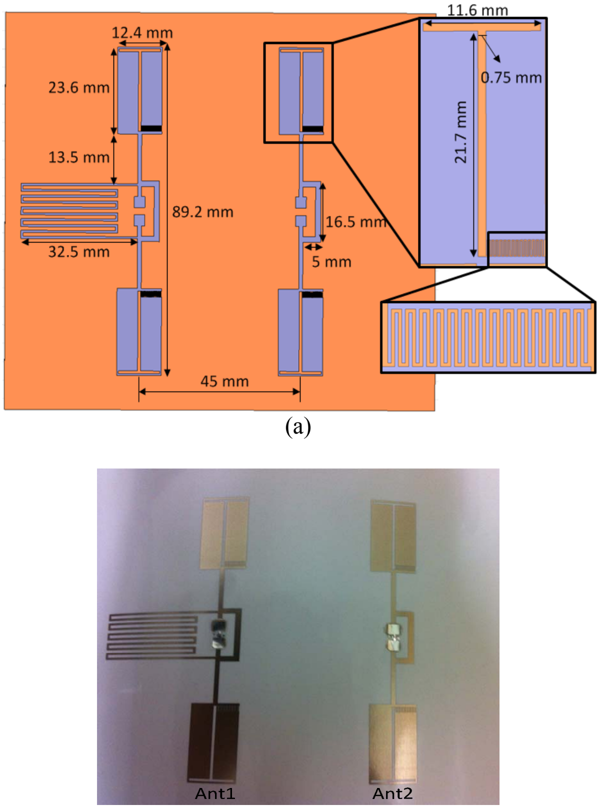

Fig. 1. (a) Geometry of the proposed capacitive RFID sensor tag . (b) Fabricated capacitive touch sensor tag by means of inkjet printing on paper substrate.

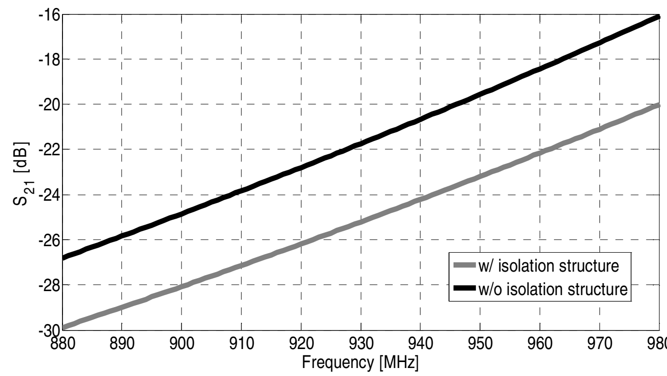

Fig. 2. Simulated S_{21} between the antennas.

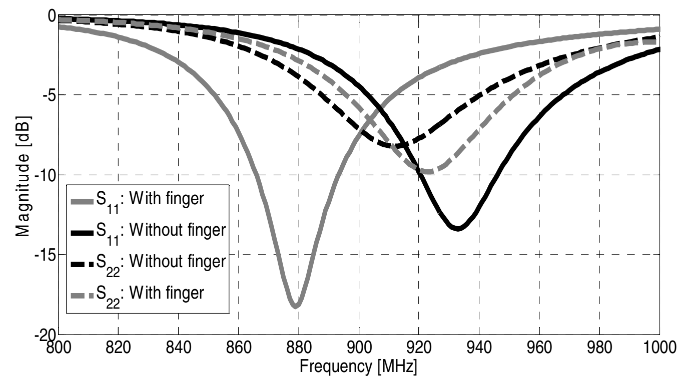

Fig. 3. Simulated input scattering parameters of the two antennas.

of approximately 915 MHz. Then a dipole-type dual antenna topology was designed and matched to off-the-shelf RFID chips using a suitable inductive loop. The total length of the antenna is 89.2 mm (0.27 $_{0}$) which is less than a half wavelength (0.5 $_{0}$) of the operation frequency of 915 MHz band while the distance of the two antennas is 45 mm (0.137 $_{0}$). The finger-to-finger gap of the interdigitated resonator is 0.1mm, while the length of each individual finger is 1.5mm, resulting in a total of 29 fingers. The capacitors of the meta-material resonator of the two dipoles are placed in such a way that the array is not symmetrical along the dipole axis, a feature which was used in [7] to further suppress mutual coupling.

Finally, a meander line is integrated to one of the two antennas as the sensing component of this capacitive sensing structure. The dimensions of the meandered line are chosen according to the following design requirements: it should not shift the antenna's resonant frequency while it should be sensitive enough to be able to sense the target event. It is designed to have the same resonant frequency as the antenna because its impedance of the meandered line is high enough to be considered as open. Furthermore, its field distribution can be easily disturbed by the presence of sensing targets. The width of the meander line is 0.6 mm and the pitch of the line is 3.2 mm. The dimensions of the proposed RFID-based sensor tag are shown in Fig. 1(a), and the fabricated sensor on paper substrate using inkjet printing technology is shown in Fig. 1(b).

The simulated isolation between the two antennas is shown in Fig. 2, where it is shown that the mutual coupling between them is reduced by 3 dB due to the effect of the meta-material inspired resonators and the meandered line. Optimization of the relative location of the interdigitated capacitors can be used to further improve isolation [7], however the obtained value was deemed adequate due to the results on Fig. 3 explained in the next paragraph.

The resonance frequency of the antenna with the meandered line (Fig. 1(b): Ant1) is strongly affected by the variation of the capacitance of the meandered line due to loading effects. Therefore, the resonance frequency will change when some material of high dielectric constant ($_{r}$) and loss tangent (tan) such as a human finger is close to the meandered line. However, the antenna without the sensing component (Fig. 1(b): Ant2) maintains its original resonance frequency since the isolation of those two antennas is high. Therefore, the presence of the high dielectric constant and lossy material can be detected once the tag is interrogated by a reader since the tag returns two different frequency responses. This is demonstrated in Fig. 3. The two antennas have a very similar frequency response (S_{11}) before the human finger touches the meandered line (no event). Nevertheless, the resonance frequency of the antenna 1 is shifted to lower frequency due to loading effect of the human finger model (event occurring)

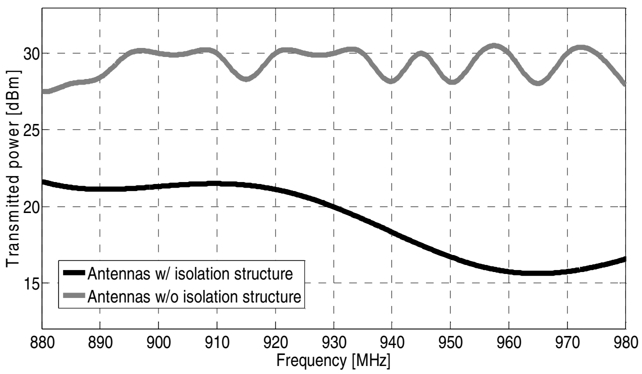

Fig. 4. Measured minimum transmitted power of 2x1 RFID antenna array with/without meta-material inspired isolator.

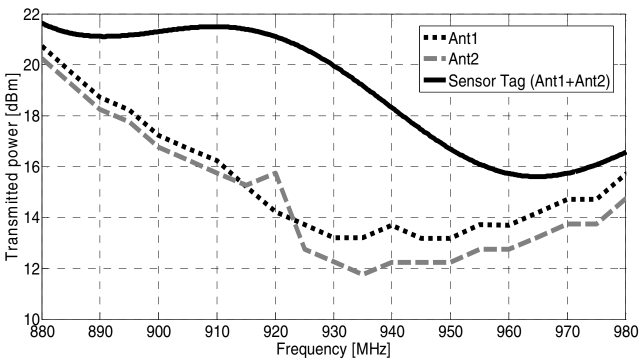

Fig. 5. Sensitivity analysis: minimum required transmitted power for activating individual tag (ant1, ant2) and the sensor (ant1+ant2).

while the antenna 2 keeps almost the same frequency response.

III. Experimental Results

The proposed RFID-based sensor tag is inkjet-printed on paper substrate and it is comprehensively tested. The properties of inkjet-printed silver nano-particles and paper substrate were thoroughly studied in previous works [8][9]. The RFID sensor was measured in the anechoic chamber and placed 60 cm away from a circularly polarized panel antenna which has 8 dBi gain. The Voyantic Tagformance reader was utilized in all measurements. The first experiment was isolation analysis varying the interrogation frequency. The minimum power required to activate the RFID chip was recorded at different frequencies in the 880 MHz ~ 980 MHz bandwidth. Fig. 4 shows the comparison between the RFID antennas with and without the meta-material inspired isolator. The 2x1 antenna array with isolator was easily readable while the 2x1 antenna array without isolator was barely readable. In the second measurement (Fig. 5), each tag (ant1, ant2) is interrogated individually, and it is compared to the measurement result of the proposed RFID-based sensor tag (ant1+ant2). The tag1 and the tag2 had almost the same

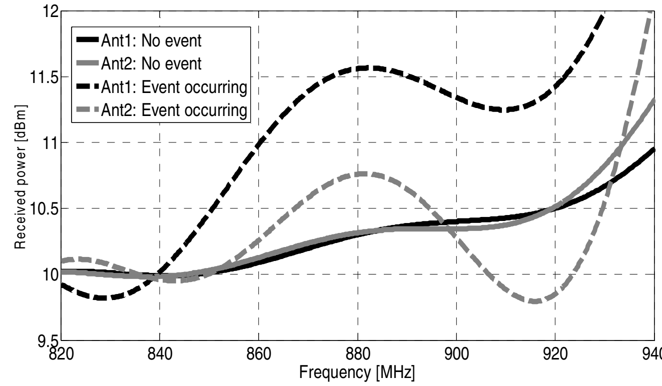

Fig. 6. Measured reflected power from the sensor each element before/after event occurring.

sensitivity, while the proposed sensor tag was readable even though the both antennas were placed side by side.

Finally, the received power from the RFID-based sensor tag was measured (Fig. 6). The array was interrogated with 20 dBm power and the received powers of the back-scattered signals from each tag antenna were recorded before/after an event occurred. When there is no event, both tags in the sensor are scattering back almost the same power, which means their antenna performance was almost identical. However, a significant difference in the back-scattered power from the two tags is observed upon the occurrence of events such as touch. This result successfully demonstrates the feasibility of the proposed sensing mechanism and its excellent potential for capacitive sensing as well as other Internet of Things applications.

IV. Conclusion

In this paper, a novel flexible RFID-based sensor tag with two metamaterial-inspired antennas and two RFID IC's has been introduced. The measurements demonstrate the sensing capability of the proposed sensor with high isolation using only one fixed operation frequency. One of the main applications for this is a touch sensor but this can be extended to any other capacitive sensors configuration such as liquid level detection, soil moisture and ambient humidity sensing.

Acknowledgement

The work of S. Kim, and M. M. Tentzeris was supported by NSF, and IFC/SRC. The work of Y. Kawahara, S. Kim, and M. M. Tentzeris was supported by New Energy and Industrial Technology Development Organization (NEDO). The work of A. Georgiadis and A. Collado was supported by EU Marie Curie FP7-PEOPLE-2009-IAPP 251557 and by the Spanish Ministry of Economy and Competitiveness project TEC 2012-39143.

References

[1] A. P. Sample, D.J. Yeager, and J. R. Smith, “A capacitive touch interface for passive RFID tags,” *2009 IEEE RFID*, pp. 103-109, April 2009.

[2] Y. Kawahara, H. Lee, and M. M. Tentzeris, “SenSprout: Inkjet-printed soil moisture and leaf wetness sensor,” *Ubicomp’12*, pp. 545, Sep. 2012.

[3] D. Girbau, A. Lazaro, and R. Villarino, “Passive wireless permittivity sensor based on frequency-coded chipless RFID tags,” *2012 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1-3, June 2012.

[4] S. Preradovic, N. Kamakar, and E. M. Amin, “Chipless RFID Tag with Integrated Resistive and Capacitive Sensors,” *2011 IEEE APMC Proc.*, pp. 1354-1357, 2011.

[5] R. Bhattacharyya, C. Floerkemeier, and S. Sarma, "Towards tag antenna based sensing - An RFID displacement sensor," *2009 IEEE International Conference on RFID*, pp.95-102, 27-28 April, 2009.

[6] S. Johan, Z. Xuezhi, T. Unander, A. Koptyug, and H. E. Nilsson, "Remote Moisture Sensing utilizing Ordinary RFID Tags," *IEEE Sensors*, pp.308-311, 28-31 Oct. 2007.

[7] J. Zhu and G. V. Eleftheriades, “A Simple Approach for Reducing Mutual Coupling in Two Closely Spaced Metamaterial-Inspired Monopole Antennas,” *IEEE Antennas and Wireless Propagation Letters*, Vol. 9, pp. 379-382, May 2010.

[8] Li Yang, A. Rida, R. Vyas, and M. M. Tentzeris, "RFID Tag and RF Structures on a Paper Substrate Using Inkjet-Printing Technology," *IEEE Transactions on Microwave Theory and Techniques*, vol.55, no.12, pp.2894-2901, Dec. 2007.

[9] B. Cook, and A. Shamim, "Utilizing Wideband AMC Structures for High Gain Inkjet-Printed Antennas on Lossy Paper Substrate," *IEEE Antennas and Wireless Propagation Letters*, *In proc.*, 2012.