UHF RFID TAG DESIGN FOR AC CURRENT SENSING

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Keywords: RFID sensing, wireless sensors, Internet of Things, self-tuning tags, smart home application.

Abstract

This study reports the development of an ac current sensing technique using a capacitance sensing UHF RFID tag which is integrated with a current transformer (CT). A new tag antenna design is created to integrate with the CT housing while maintaining the tag link. The terminals of the capacitance sensing RFID chip are connected to a tuning circuit with a reactance controlled by the current flow in the primary of the CT. A prototype tag was tested to validate the battery-free compact tag that streams current measurement data over a read range of about 5 m using the European RFID UHF band at 868 MHz. The tag could be used for wirelessly sensing the load current of an individual domestic appliance and where a single reader could simultaneously monitor multiple tags, enabling smart reading of electricity consumption across multiple devices in smart homes.

1 Introduction

Energy demands have significantly increased across the world in the recent decade [1]. The commercially available energy monitoring tools provide a platform for tracking the power consumption of individual appliances at homes and transmit real-time electricity readings to a display unit. This offers possibilities to avoid unnecessary energy usage in homes. Engaging householders with the live data of energy consumption (kW and cost) in a display unit could aid them to cut energy cost and usage.

However, there are some complications related to the implementation of the active smart meters at homes, such as installation problems and cost as well as maintenance. There is a need to develop new affordable and easy-to-install passive energy monitoring tools to resolve these issues. The RFID technology has a good potential in this application context as it can offer a passive, low-cost and easily accessible sensing solution [2].

Prior studies have reported the application of UHF RFID systems for sensing of activity of domestic electrical appliances. These studies explored the use of tags integrated with an impulse acquisition block and a magnetic circuit for detecting the ON and OFF status of electrical devices. One study demonstrated an application by wrapping a power cord with a flexible dipole RFID antenna connected to an impulse sensing board [3]. Similarly, in another study, a flexible helix antenna was bent around the power cable [4]. A different approach was demonstrated in a study where a RFID tag was coupled with a magnetic sensor for wireless sensing of home electrical devices [5]. However, these mechanisms are only suitable for checking the ON and OFF status of electrical devices and are unable to monitor the real-time ac load current of an electrical device which is essential for smart power monitoring system.

This paper presents a novel UHF passive RFID tag design for ac current sensing. The tag contains a self-tuning RFMicron Magnus S2 transponder chip and linked with tuning circuit and Current Transformer (CT). The sensor would be useful for measuring the load current of each appliance by a single RFID reader at future smart home and industry 4.0.

The paper describes the sensing system, the design and simulation process, the experimental results and scope for future work.

2. Sensing System

The design of the proposed tag system is shown in Fig. 1. It consists of three key elements: (i) a current transformer, (ii) a tuning circuit, and (iii) a capacitance sensing passive UHF RFID tag. The CT senses ac current from the power cable and outputs a voltage that is linearly proportional to the input current. The CT feeds a tuning circuit which is employed to detune the impedance applied to the tag chip. The tag generates a 5-bit sensor code which represents the degree of change in capacitance across the tag antenna terminals which in turn is a function of applied voltage from the CT.

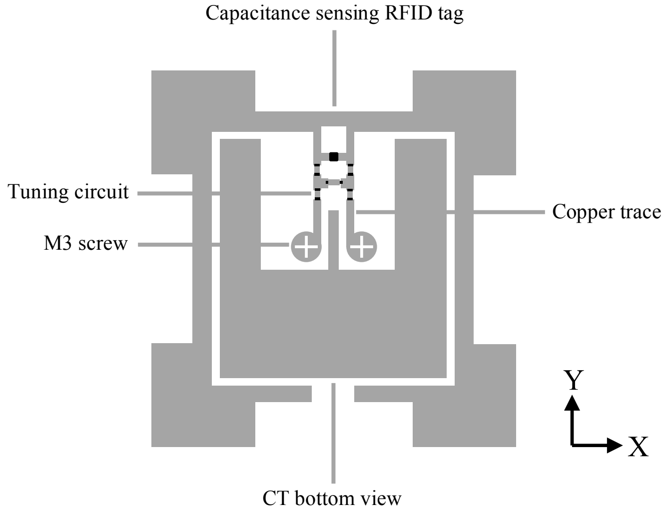

Fig. 1. Schematic diagram of the proposed system.

2.1 Current Transformer

The split-core current transformer [6] can detect ac current in the range of $0-10$ A and transform it to $0-10$ V dc proportionally. The transformer has a full-scale accuracy of ±2% with the operating frequency of 50/60 Hz. The CT comes with two M3 screw terminals, which were used to connect the CT with the tuning circuit.

2.2 Tuning Circuit

The tuning circuit was designed consisting of two inductors of 500 nH, a varactor diode [7] and two 15 pF capacitors. The relationship of the reverse voltage and capacitance of the tuning diode is derived from the varactor diode datasheet [7]. The capacitors block the dc voltage to avoid degradation in the performance of the RFID chip and inductors are used as RF chokes. The input terminals of the tuning circuit were connected to the CT, while the output terminals of the tuning circuit were linked to the tag antenna terminals. Two 10 mm long, 1 mm wide copper straps with a 4 mm gap connect to the voltage from the CT, Fig. 1. Fig. 2 illustrates the schematic diagram of the tuning circuit linked to the tag. The tuning circuit used 0603 size components with a pitch of 0.5 mm between contacts, and was fabricated along with the RFID tag on a 0.18 thick Mylar substrate.

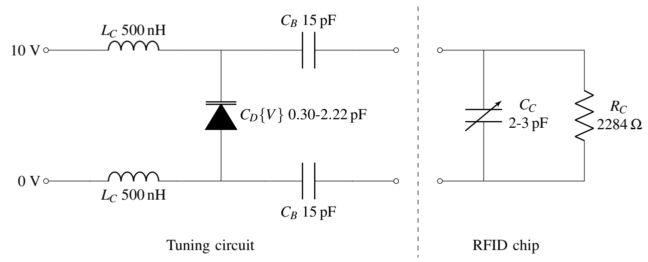

Fig. 2. Schematic diagram of the tuning circuit and the RFID chip.

2.3 RFID Tag Antenna

The tag antenna was designed to achieve compact physical integration with the CT housing, as well as achieve good read range. The antenna design (Fig. 3) has a square form factor with a central space for the CT. The antenna was simulated with Computer Simulation Technology (CST) Microwave Studio [8]. The simulation included the Mylar substrate with a dielectric constant (ε_r) of 2.8, loss tangent (tan δ) of 0.003 and thickness of 0.18 mm including the copper thickness of 0.04 mm. The RFMicron S2 chip [9] requiring input power -16.1 dBm and the impedance of 2-3 pF in parallel with 2284 Ω was used. The chip covers all worldwide UHF bands (860-960 MHz).

The total capacitance for the tag antenna is:

$$C_T(n) = C_{min} + nC_o \quad (1)$$

where $C_T(n)$ is the total capacitance, C_{min} is the minimum capacitance of 2 pF of the microchip, n is the sensor code in the range of 0-31 and C_O is a tunable step (1 pF/31) within the 1 pF tunable range. Therefore, for simulations, the antenna impedance was matched with the microchip impedance of $1.63 - j\,61.07\ \Omega$, at 868 MHz. A capacitor of 0.3 pF was attached across the antenna terminal which represents the minimum capacitance of the tuning circuit. When the independent tag antenna was simulated, a good match was achieved at the UHF RFID band with S_{11} of -23 dB at 862 MHz as illustrated in Fig. 5.

To assess the impact of the CT on the tag performance, the current transformer [6] was included in the CST antenna model, Fig. 4. The reflection coefficient S_{11} of the tag mounted on the CT is illustrated in Fig. 5. The simulated results show that the resonance frequency of the tag shifted from 862 MHz to 838 MHz when the tag was attached to the CT.

The simulated radiation patterns are shown in Fig. 6 indicate the tag and the tag mounted on the CT has a gain of 1.1 dB and 1.4 dB, respectively, at 868 MHz. Furthermore, the tag simulated radiation efficiency was -0.324 dB and the radiation efficiency of the tag mounted on the CT was -0.0171 dB.

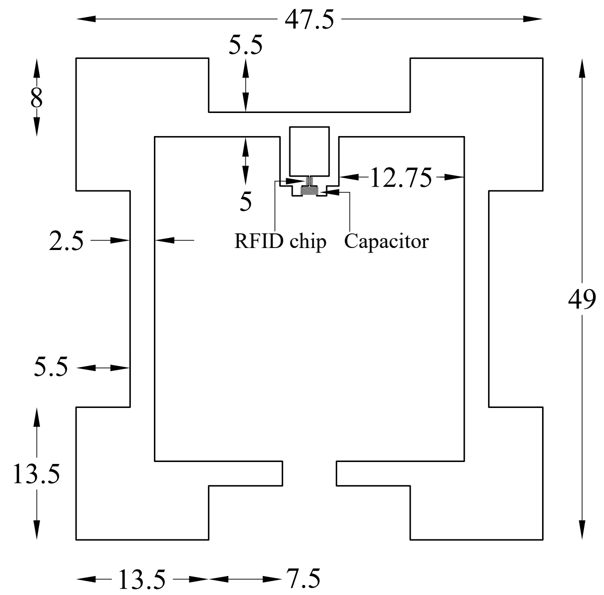

Fig. 3. Proposed RFID tag geometry. (Dimensions in mm)

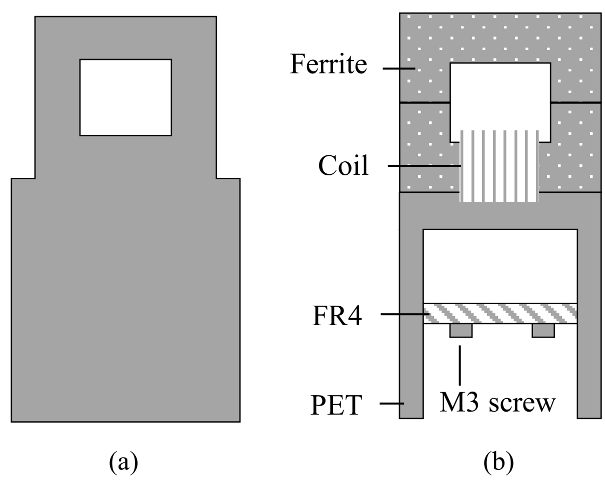

Fig. 4. (a) Outside shell and (b) inside components of the CT as used for simulations.

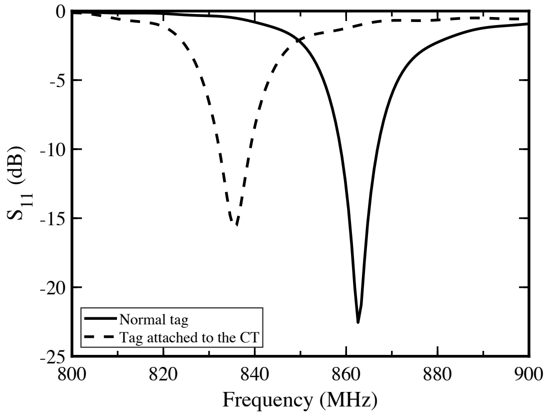

Fig. 5. CST simulated S_{11} of the RFID tag.

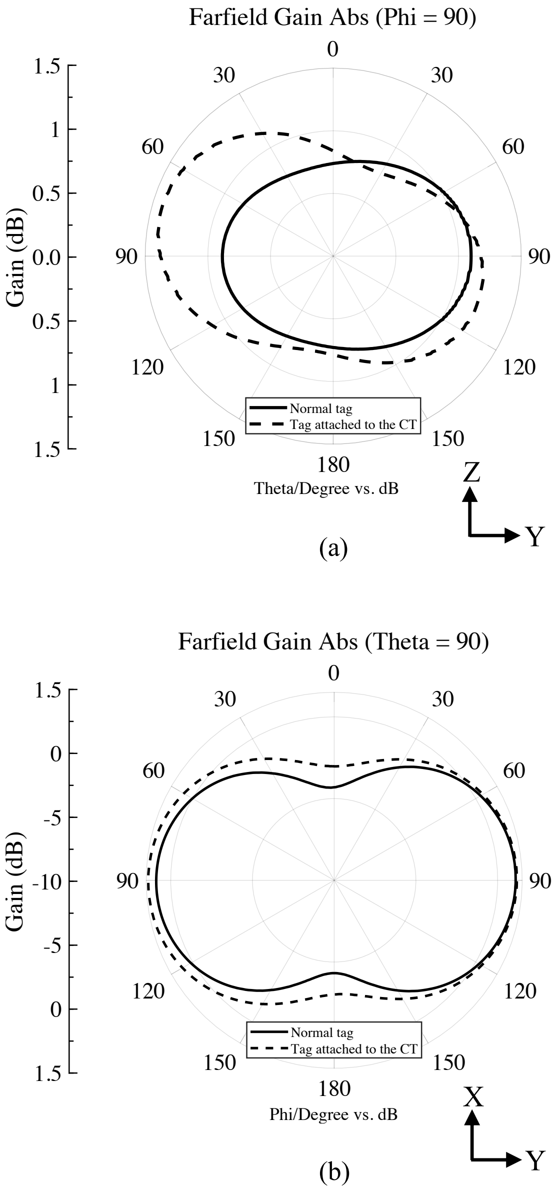

Fig. 6. Polar plot of CST simulated tag gain (excluding input reflection loss) (a) y-z plane, (b) azimuth plane.

3 Experimental results

3.1 Tag Read Range

The tag was experimentally interrogated with a UHF reader Tagformance Pro System [10], comprising of a 6 dBi gain linear polarised antenna and placed a fixed distance of 30 cm away from the tag. A read range of approximately 5 m at 868 MHz was obtained, Fig. 7. The tag read range is increased with the increased frequency as the embedded self-tuning RFID chip covers all worldwide UHF bands (860-960 MHz) which increase the readability of the tag.

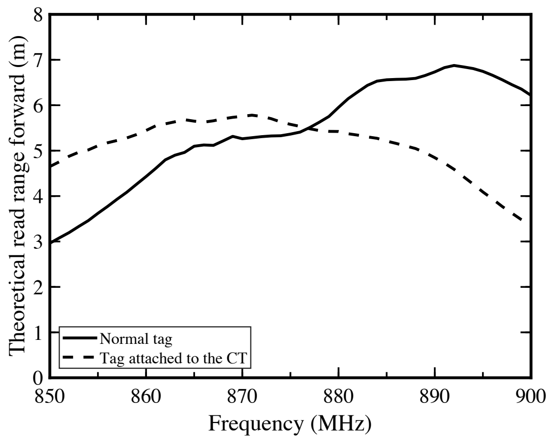

Fig. 7. Measured read range of the tag.

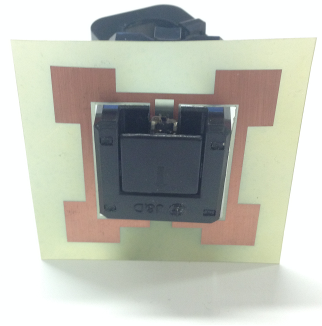

Fig. 8. A final tested prototype of the tag system.

3.2 AC Current Sensing Setup

To demonstrate the performance of the complete sensing system, the RFID tag, the tuning circuit and the CT were coupled, Fig. 8, and tested with the measurement setup which included (i) the UHF reader Tagformance Pro System to interrogate the tag system. (ii) the split-core CT clamp around a single current carrying wire, enclosed in the insulating box (iii) an electrical heater with an adjustable heating setting (low and high) as an electrical load, (iv) a commercial Brennenstuhl PM 231 E current meter with ±1% accuracy [11] to benchmark the tag results.

3.2 Current and Sensor Code Relationship

Fig. 9 shows the measured sensor code for high, low and zero current levels. The sensor value for 9.4 A and 4.7 A was 10 and 6 respectively where the electric heater consumed 2.2 kW at high setting and 1.1 kW at low setting. Fig. 10 gives the read range of the sensor for each current level. The lowest read range was recorded at 0 A, because the tag is out of tuning range as the tuning varactor capacitance reached to its maximum value. There is a decrease in the read range of the tag system as compared to the read range of the normal tag shown in Fig. 7, as the losses occur due to the tuning circuit attached to the tag.

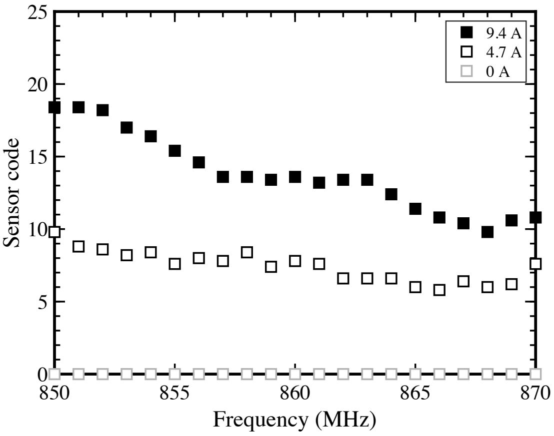

Fig. 9. Sensor code variations as the current flow changes in power cable.

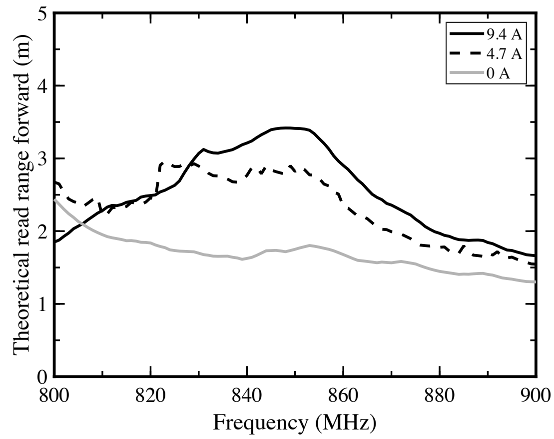

Fig. 10. Read range of the proposed tag system.

4 Conclusion

A UHF RFID ac current sensor has been demonstrated which enables low-cost ac sensing of individual appliances in a smart home. A UHF RFID tag, a tuning circuit and a current transformer were integrated to develop the sensing system. The sensor was experimentally tested with a switchable electric load. The tag transmitted 5-bit sensor value which represents the ac current drawn by the electric load. The sensor is small-in-size, easy-to-install and cost-effective solution for small ac current sensing based on the UHF RFID system. The tag would be able to read ac current from the power cord and wirelessly report readings of a measured load current to a dedicated RFID reader.

The object of the future work is to modify the tag antenna design to achieve the centre resonance frequency 868 MHz when the tag is integrated with CT and to increase the read range of the sensor at 868 MHz.

5 Acknowledgements

The INCASE project is part-funded by the European Commission as part of the 2Seas Intereg V Programme. We would like to thank Antonio Mendoza for fabricating the tags.

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