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LETTER

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RFID antenna humidity sensor co-design for USN applications

Yasar Amin[a)], **Yi Feng, Qiang Chen, Li-Rong Zheng, and Hannu Tenhunen**

iPack VINN Excellence Center, Royal Institute of Technology (KTH)
Isafjordsgatn 39, Stockholm, SE-16440, Sweden

a) *ysar@kth.se*

Abstract: We demonstrate for the first time an RFID tag antenna which itself is humidity sensor and also provides calibration functionality. The antenna is comprised of T-matching network and horizontally meandered lines for impedance matching and reliable near-field communication. The novel contour design provides humidity sensing, and calibration functions whilst concurrently acts as a radiating element along with quadrangular capacitive tip-loading with covered middle portion for far-field communication. The inkjet printed prototypes of the antenna provide effective ambient humidity sensing while demonstrating stable RFID communication. The antenna has a compact size of 1.1×10.2 cm for 902–928 MHz band.

Keywords: RFID antenna, humidity sensor, sensor calibration, inkjet printing, flexible electronics

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

In the Internet-of-Things paradigm (IoT), selective information from any item of a certain value is on the network in one form or another. Radio frequency IDentification (RFID) and sensor network technologies are giving fuel to this evolving standard. RFID faces several critical challenges of cost, reliability and eco-friendliness when evaluating, planning and implementing it for most exciting unfolding era of Ubiquitous Sensor Networks (USN). However, the present sensor-enabled RFID solutions downgrade their effectiveness on account of extra cost [1] by employing additional components or materials [2, 3, 4] to achieve sensor module. Likewise, the vast fated implementation of sensor nodes demands a design with the capability of customizable calibration function in order to replicate it without additional costs.

This paper presents an RFID tag antenna with embedded functionality as a humidity sensor along with calibration options realized through distinctive structural properties. The proposed compact antenna is directly printed on commercially available paper substrate for realizing the eco-friendly and ultra-low cost USN module. The accumulative effect of humidity on electromagnetic properties of paper substrate and conductive pattern, which constitute the RFID tag is explored to determine the antenna performance under various operating humidity levels. The proposed antenna has extended read range, and wider operational bandwidth for catering the manufacturing disparities while at the same time provides an extra level of liberty for sensor calibration.

2 Antenna design and optimization

The preeminent step in paper substrate usage is to characterize its properties, which varies considerably among commercially available papers. The substrate adopted is Kodak photopaper of 250 μm thickness (280 gm/m^2) with dielectric constant and loss tangent of 3.3 and 0.077 respectively, extracted by using ring resonators method. NXP UCODE G2XM RFID Al-strap is selected, for instance the goal IC impedance at 915 MHz is 13.3–j122 Ω is preferred. However, the principle of operation for the proposed antenna is not IC dependent. RFID radar cross section is important for reflecting passive tags. In this case, the RFID contains a resonating structure that reradiates when illuminated by the reader. The detectability of the tag depends on the RCS (or backscattered field) returned by the tag. The RFID reacts to the incident power density generated by the reader:

$$S = \frac{P_t G_{reader}}{4\pi r^2} \tag{1}$$

Here S is the power density in Watts/m^2, P_t is the total transmitted power by the reader, G_{reader} is the reader's antenna gain, and r is the distance between the reader and the RFID tag. If the tag's antenna has an effective aperture, A_e, its received power at the antenna terminals is then $P_a = SA_e$. This becomes the input power to the circuit powering the tag's circuit. Thus, one of the optimization factors is to achieve optimal antenna

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effective aperture in contrast to previous approaches in which one dimensional methodology is adapted to simply improve the antenna gain. As we are impending towards eco-friendly tags, every drop of ink saved in manufacturing process plays a vital role. The reradiated power P_{re} due to P_a can then computed as:

$$P_{re} = KP_a G_{tag} = \frac{4R_a^2}{|Z_a + Z_c|} \cdot P_a G_{tag} \tag{2}$$

Where, G_{tag} is the tag's antenna gain and K is the ratio of reradiated to incident energy with $R_a = \Re\ (Z_a)$, where Z_a is the complex antenna input impedance.

It is observed that a short circuited tag $(Z_c = 0)$ reradiates 4 times more power than a conjugate matched one $(Z_a = Z_a^*)$. It is also noted that, in the case of conjugate matching, the tag absorbs and reradiates equal amounts of power. In general, the tag radar cross section, σ, is used to measure the radiation effectiveness. Specifically, in evaluating the RFID's effectiveness, the ratio of the returned to transmitted power is of interest.

$$\sigma = \frac{P_{re}}{S} = KA_e G_{tag} = \frac{\lambda^2 G_{tag} G_{reader} {R_a}^2}{\pi |Z_a + Z_c|^2} |\hat{p}_{reader} \cdot \hat{p}_{tag}|^2 \tag{3}$$

Here $\hat{p}_{reader}$ and $\hat{p}_{tag}$ refer to the corresponding antenna polarizations. Clearly, the tag antenna gain plays a major factor; therefore, several iterations are carried out to address this challenge for achieving an efficient tag antenna design as showed in Fig. (1).

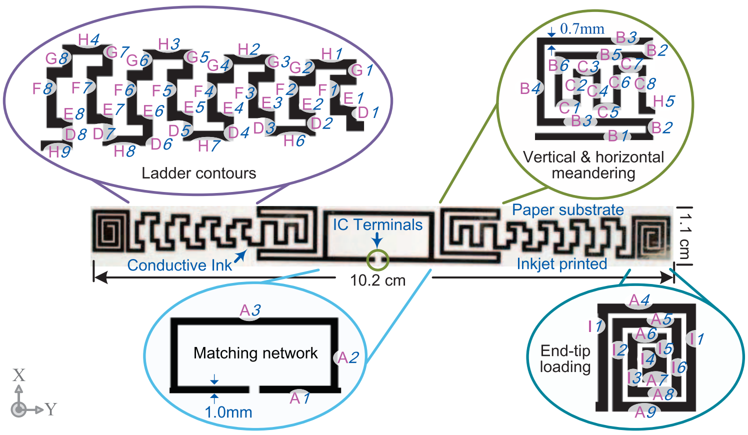

Fig. 1. Geometry of RFID sensor antenna.

3 Antenna as a sensor design

In order to achieve humidity sensor, the proposed antenna has to demonstrate linear parametric changes in response to paper dielectric variations which in-turn corresponds to calibrated relative humidity levels. The main challenge at this stage is to realize an antenna structure which remains detectable inspite of its parametric changes, which are eventually transformed into sensor

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data. These limits motivated towards an antenna design, which has complex combination of five classifiable elements for providing stability as well as changeability in order to manifest sensory, and radiating characteristics simultaneously.

Table I. Antenna structural dimensions.

(mm)	A	B	C	D	E	F	G	H	I
1	9.69	12.3	2.47	0.44	1.89	3.1	0.43	3.62	6.93
2	9.24	0.77	2.44	0.46	1.89	3.3	0.51	3.62	5.77
3	19.18	11.2	2.65	0.51	1.89	3.5	0.58	3.57	3.46
4	7.15	7.70	2.82	0.66	1.84	3.7	0.66	3.57	1.92
5	5.00	7.85	2.65	0.74	1.84	3.9	0.74	3.16	2.31
6	2.86	4.18	2.19	0.81	1.84	4.2	0.81	3.62	4.62
7	1.78		3.16	0.89	1.84	4.4	0.89	3.62	
8	3.93		3.56	0.97	1.84	4.6	0.97	3.57	
9	6.10							3.57	

The computer-aided design of the antenna is accomplished by using the commercial full-wave simulator ANSYS HFSS$^{\mathrm{TM}}$. As showed in Fig. (1), the inner loop (composed of the series and shunt stubs) formed by T-matching network ($A1$–$A3$) is effective for stable near-field operation. It mainly optimizes and contributes to the input impedance matching in collaboration with progressive and horizontal meandering structures constituted by segments B–C. The novel progressive ladder contours formed by varying lengths of D–H segments, play the indispensable function of fine-tuning the slope of impedance curve in customizing the sensor calibration. It is discerned that the coupling between electromagnetic characteristics of the paper substrate and radiating elements is considerably aided by these contours. The coupling features and stabilized performance in the far-field region are likewise enhanced by quadrangular capacitive-tip loading, and the area of the middle plate structure by adjusting the length and spacing of segments from $A4$–$A9$ & I. It is pragmatic, this added capacitance is approximately proportional to the perimeter of the loading shape rather than its area.

4 Fabrication process

The prototype antenna is directly printed on paper (Fig. 1) by using Fujifilm Dimatix DMP2800 tabletop printer by depositing silver nano particles based ink (CCI-300) by Cabot Corp., which has alcohol-based vehicle and contains 19–21% weight of nano-silver particles of less than 50 nm diameter. This ink is selected due to the large ratio of the area to volume of its nano particles, which exhibit significantly lower melting point and provides stability against humidity effects. Each layer of printing at standard room conditions resulted in 600 nm thickness; therefore, three layers are printed by considering skin depth effect and sheet resistance. After inkjet printing, a ventilated

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thermal oven sintering for two hours at 120°C provides a continuous metal conductor of around 9x10^6 S/m conductivity, which is measured by deploying Four Probe Method along with Profilometer measurements, thus providing a percolation channel for the conduction of electrons throughout the material without obstacles. The optimized dimensions of proposed antenna with conjugately matched impedance and calibrated for measuring every 20% RH change are specified in Table I.

5 Experimental verification of antenna performance

Firstly, the antenna's electromagnetic characteristics are measured standalone in an anechoic chamber setup in which impedance is measured by using S-parameter method (with SOLT calibration procedure), whereas the return loss and radiation patterns are measured by employing Half-Mirror method in combination with SOL calibration procedure for achieving elevated measurement accuracy. The near and far-field operational characteristics of the proposed RFID tag are verified using Impinj's UHF RFID reader kit. The effect of humidity variations on antenna parameters is characterized using climate chamber (Weiss Technik WK 11-180), and for validating results under normal room conditions, measurements are also carried out in the anechoic chamber by using humidifier and hygrometer while keeping the fixed distance between the RFID reader and the proposed sensor tag. The computed and measured impedance variations of the antenna in response to varying humidity levels are plotted in Fig. 2 (a). The resistance and reactance show controlled linear behavior with overall 8% and 9% variation, respectively between two extremes. The measurements are repeated several times for extracting reliability parameters and validating the sensor functionality.

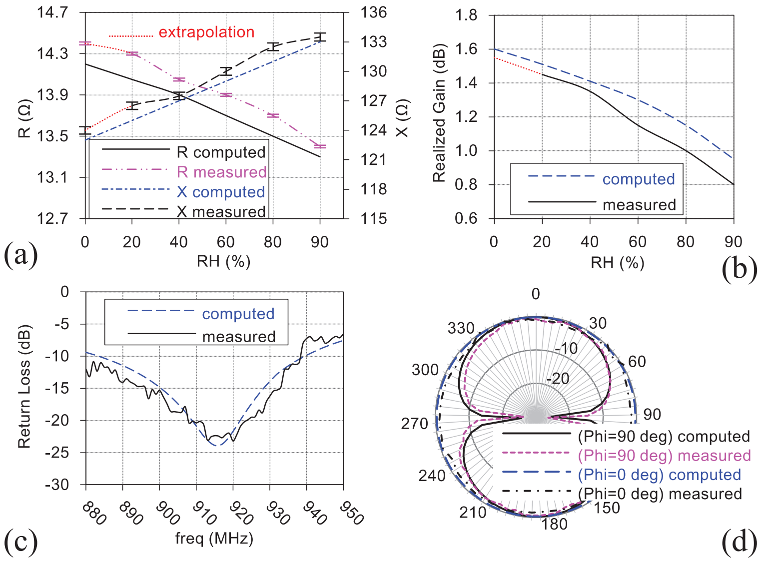

Fig. 2. (a) Resistance and reactance variation @915 MHz; (b) gain variation due to change in humidity level; (c) measured and computed return loss; (d) radiation patterns of RFID sensor antenna at 915 MHz.

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Furthermore, the calibration capability on the tag side in accordance with substrate for implementing self-effacing and more reliable procedures to formulate the absolute humidity sensing system. The impedance variation with respect to relative humidity levels in-turn causes the variation in antenna gain, which is revealed in Fig. 2 (b), and consequently, the backscattered power received while tag is placed in boresight of the RFID reader varies which is appropriately calibrated to ascertain the relative humidity (RH%) change. The antenna exhibits better return loss, which is larger than −15 dB as showed in Fig. 2 (c). The distortion is maybe due to the effect of metal ground fixture used for half-mirror method, and can be eliminated or significantly minimized by employing a metal plate with more rounded edges. Fig. 2 (d) shows the normalized computed and measured 2D radiation patterns which are nearly uniform (omnidirectional) at 915 MHz. Thus, a good agreement is pragmatic between the computations and measurements, which can similarly be substantiated for other frequencies within the antenna's bandwidth. The proposed sensor tag demonstrates extended portable read range of 11.1 m and fixed 6.7 m as a standalone RFID tag and with full humidity sensing functionality, respectively. Additionally, the gain and sensitivity against relative humidity level of the proposed antenna can be ameliorated by increasing the size depending upon particular industrial application.

6 Conclusion

An RFID tag antenna with incorporated humidity sensor characteristics, and has potential of customizable calibration, is designed, manufactured and validated. It is observed that paper type plays a pivotal role for response time in accordance with relative humidity level change. The integration of ink and paper substrate is critical for igniting the destabilization effect, which is utilized in a controlled mechanism by the structural configuration of the proposed antenna, and also inventively provides the effective calibration of the humidity sensor in accordance with defined desiderata. Likewise, the same phenomenon is achieved by using Kapton-HN as substrate which broadens the applicability of the proposed design. Furthermore, the proposed sensor-based RFID tag is eco-friendly, versatile and economical, thus making it well suited for realizing ubiquitous sensor networks.

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