Phase-oriented Chemical Sensing by Passive UHF-RFID

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Abstract

Most of up to day efforts to extract physical information from an object where an RFID tag is attached on are based on the processing of the backscattered power reflected by the tag and collected by the reader. This contribute investigates, for the first time, the use of the *phase* of the reflected field to derive quantitative information about chemical variations of the environment, nearby the tag. The proposed methodology is described throughout a controlled laboratory experiment involving a chemical doped RFID tag for humidity sensing.

1.Introduction

The ability to use battery-less tags as devices for sensing of objects, people and environments has become one of the most interesting and promising trend of passive UHF RFID technology, with applicability to the emerging paradigm of Internet of Things and implementation of Ubiquitous Sensing [1]. A passive RFID system comprises a digital device called tag, embedding an antenna and an IC-chip with a unique identification code (ID), and a radio scanner device called reader. Tags can be used as real sensors, exploiting the clear dependence of the tag antenna's radiation characteristics on the tagged object and on the nearby environment. The tag's response to the incident electromagnetic field emitted from the reader, can be in fact modulated by loading the antenna with Chemical Interactive Materials (CIM) that are sensitive to physical/chemical variations of the environment. Such materials, on interacting with the target molecules, modify their electrical properties and induce changes in impedance and gain of the overall tag antenna [2]. Up to date, the electromagnetic parameters involved in UHF RFID sensing include the turn-on power, i.e. the lowest input power emitted by the reader required to activate the tag, the backscattered power from the tag to the reader, and the Analog Identifier (AID) [1] which depends only on the antenna's impedance module. Nowadays most of the RFID readers are able to perform a fully coherent detection from which it is possible to extract the phase of the demodulated signals backscattered by the tag [3]. Nevertheless, the study of the phase is still an unbeaten track, since for many readers this information is not made available to the users. The few experiments with the phase processing have been until now mostly focused to spatial identification, e.g. to get information about speed and position of tagged objects and persons [4].

This work investigates theoretically and experimentally the possibility to process the phase of the backscattered signal at UHF frequency to detect and quantify the change of volatile compounds by using a CIM-doped tag. A model of phase variation is presented that is useful to estimate the sensor's capability and to shape its response. Thanks to the great extension of the phase range, the phase-based sensing could be used both complementarily and in synergy with the more assessed power-based sensing in order to improve the resolution and the overall reliability of the sensing.

2. Phase representation of the backscattered field

According to [5] the backscattered signal from the tag collected at the reader's load (assumed in perfect impedance matching condition), can be written as

$$V_L = -\frac{1}{2}\underline{h}_R \cdot \underline{E}_s = -\frac{1}{2}\underline{h}_R \cdot \underline{E}_0^{OC} + \frac{\eta_0}{k_0^2} G_R \sqrt{\frac{P_{in} R_R^{in}}{2}} g^2 \left(\frac{1}{Z_A + Z_C}\right) \frac{e^{-2jk_0 r}}{r^2}, \qquad g = \sqrt{\frac{R_A^{in} G_{tag}(\underline{\hat{r}})\chi}{\eta_0}} e^{j\phi(\underline{\hat{r}})} \tag{1}$$

where $\underline{h}_R$ is the effective length of the reader antenna; $\underline{E}_s$ is the backscattered field, given by the combination of the structural mode $\underline{E}_0^{OC}$ and the antenna mode; $\eta_0 = 120\,\pi\,\Omega$ is the vacuum characteristic impedance; k_0 is the propagation constant; G_R is the gain of the reader antenna; P_{in} is the power emitted by the reader; R_R^{in} is the input resistance of the reader antenna; r is the reader-tag distance; $Z_A = R_A + jX_A$ is the tag impedance; $Z_C = R_C + jX_C$ is the IC impedance; g is the normalized gain of the tag with R_A^{in} internal resistance and $G_{tag}(\underline{\hat{r}})$ is the gain of the tag antenna.

The polarization mismatch effects between the effective length of the field radiated by the reader $\underline{\hat{h}}_R(-\underline{\hat{r}})$ and the effective length of the tag $\underline{\hat{h}}_{tag}(\underline{\hat{r}})$ are given by the amplitude $\chi = \left|\underline{\hat{h}}_{tag} \cdot \underline{\hat{h}}_R\right|^2$ and the phase $\phi(\underline{\hat{r}}) = angle(\underline{\hat{h}}_{tag} \cdot \underline{\hat{h}}_R)$. The backscattering modulation imposes that the microchip's RF impedance Z_C switches between two states: Z_C^{ON} and Z_C^{OFF} and accordingly the received signals will be

$$V_L^{ON/OFF} = -\frac{1}{2}\underline{h}_R \cdot \underline{E}_0^{OC} + \frac{\eta_0}{k_0^2} G_R \sqrt{\frac{P_{in} R_R^{in}}{2}} g^2 \left(\frac{1}{Z_A + Z_C^{ON/OFF}}\right) \frac{e^{-2jk_0 r}}{r^2} \tag{2}$$

The phase of the signal backscattered from the tag and retrieved by a commercial reader is defined by [3] as $\varphi = \arg(V_L^{OFF} - V_L^{ON})$ that after simple mathematic calculation can be written as

$$\varphi = -2k_0 r + 2\phi(\underline{\hat{r}}) + \arg\left(\frac{1}{Z_A + Z_C^{OFF}} - \frac{1}{Z_A + Z_C^{ON}}\right) \tag{3}$$

The phase is therefore composed of three contributes: $-2k_0 r$ is the propagation term accounting for the dependence on the distance r between reader and tag; $2\phi(\underline{\hat{r}})$ is the polarization term embedding the polarization mismatch between reader and tag; the last term shows instead a clear dependence of the phase on the input impedance of the tag antenna, as well on the microchip impedance switch $Z_C^{ON/OFF}$. By assuming that the antenna's impedance is subjected to changes over time due to a physical/chemical variation, and denoting with $\varphi(0)$ a reference state, then the equation of phase-based sensing is

$$\Delta\varphi(t) = \varphi(t) - \varphi(0) = arg\left(Y_{tag}^{OFF}(t) - Y_{tag}^{ON}(t)\right) - arg\left(Y_{tag}^{OFF}(0) - Y_{tag}^{ON}(0)\right) \tag{4}$$

with $Y_{tag}^{ON/OFF} = \left(Z_A + Z_C^{ON/OFF}\right)^{-1}$ the overall tag admittance.
The above equation can be made more specific to a chemical RFID sensor already presented by the authors in [2] for humidity detection that will be used for numerical and laboratory experimentations. The radio-sensor consists of a planar miniaturized doubly folded patch antenna on a Forex substrate, provided with a central radiating slot wherein the microchip is placed (Fig. 1A). The surface electric field strength is maximum inside the slot itself and hence a drop of CIM can be painted in the sensing niche close to the microchip to functionalize the tag for volatile compounds sensing. Fig. 1B) shows the equivalent lumped circuit of the sensor tag for the reverse link, where the CIM is modeled [2] by the parallel connection of a humidity-dependent resistance $R_{CIM}[RH]$ and capacitance $C_{CIM}[RH]$.

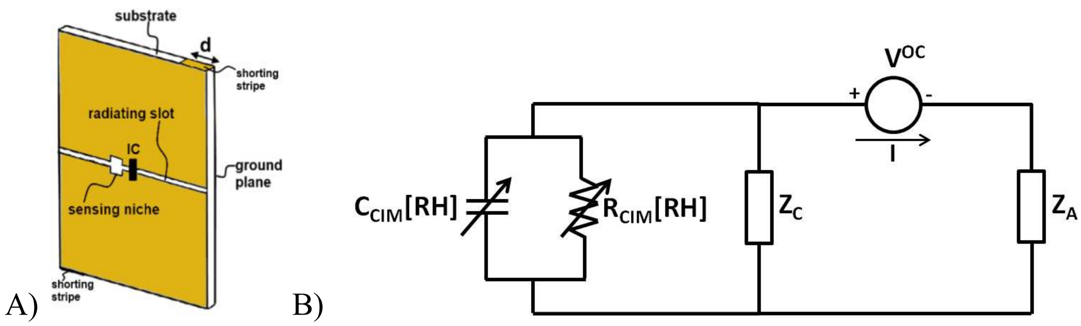


Fig. 1 A) Layout of the humidity sensor tag [2]. The CIM is deposited in the sensing niche. B) Equivalent lumped circuit for the reverse link.

The corresponding overall impedance of loaded tag is

$$Z_{tag}^{ON/OFF}[RH] = Z_A + \left(Z_C^{ON/OFF} // Z_{CIM}[RH]\right) \tag{5}$$

By assuming a reference impedance modulation $Z_C^{ON} = Z_C$ and $Z_C^{OFF} \to \infty$, the phase-based sensing equation in (4) has to be finally evaluated for $Y_{tag}^{ON}[RH] = (Z_A + Z_C // Z_{CIM}[RH])^{-1}$ and $Y_{tag}^{OFF}[RH] = (Z_A + Z_{CIM}[RH])^{-1}$.

3. Numerical Analysis

The chemical interactive material considered for this analysis is PEDOT:PSS, a hygroscopic moisture-sensitive polymer. The relationship between Pedot:PSS parameters and humidity at UHF frequencies has been borrowed from [2]:

$$\begin{cases} R_{CIM}[RH] \simeq 17 - 0.32 \cdot RH - 1.7 \cdot 10^{-4} \cdot RH^2 \\ C_{CIM}[RH] \simeq -0.31 + 0.02 \cdot RH - 1 \cdot 10^{-4} \cdot RH^2 \end{cases} \tag{6}$$

By computing the unloaded tag's impedance with numerical simulations, equations (4) and (5) permit to estimate the sensor's calibration curves for different frequencies in worldwide UHF RFID band (Fig. 2), i.e. the phase variations with respect to the change of RH normalized to the phase value at ambient humidity (RH=40%).

The dynamic ranges and the slopes of the calibration curves (sensitivities) are greatly dependent on the frequency the reader is interrogating the tag. The proposed layout is provided with an agile tuning mechanism that allows shaping the frequency response of the tag just by varying the control parameter *d* of short-circuit stripes (in Fig.1 A). Fig. 3 gives some examples of sensitivity/frequency tuning.

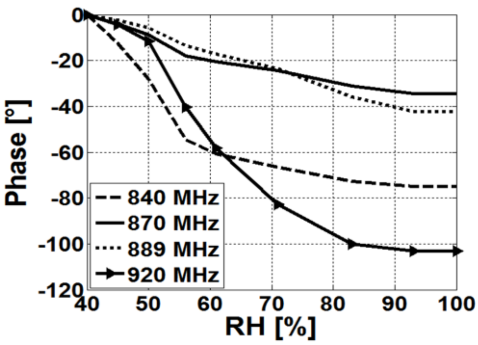


Fig. 2. Estimated calibration curves of the humidity sensor at four selected frequencies in the worldwide UHF RFID band. Phase variations of the backscattered signal are represented as a function of humidity.

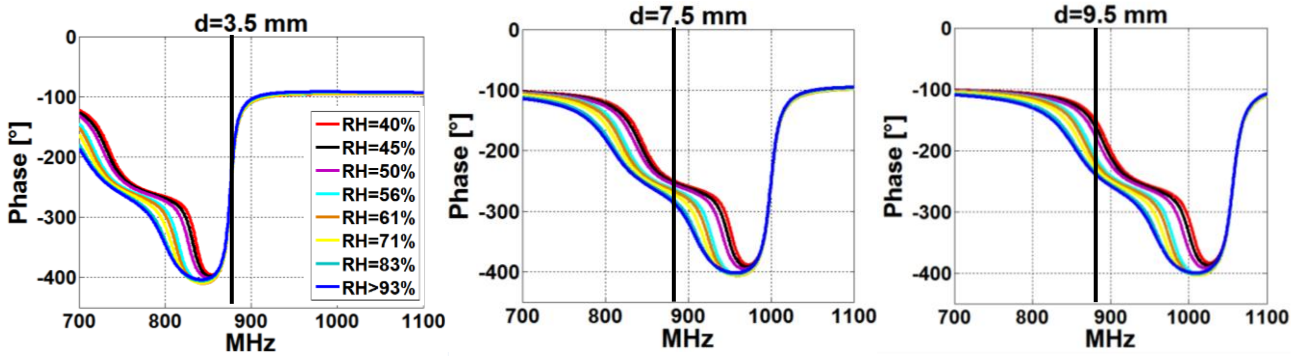


Fig. 3 Phase variations vs. humidity and frequency for three lengths of the tuning parameter *d*. In each graph the vertical line indicates the European RFID frequency.

4. Laboratory Experimentation

A prototype of the sensor tag (Fig. 4A) was fabricated with the same dimensions as in [2] (having fixed the tuning parameter *d*=7.5mm) in order to validate the proposed model and sensing methodology with an experimental characterization. The humidity sensor's performance was analyzed dynamically when the humidity gradually was changing from ambient condition up to saturation.

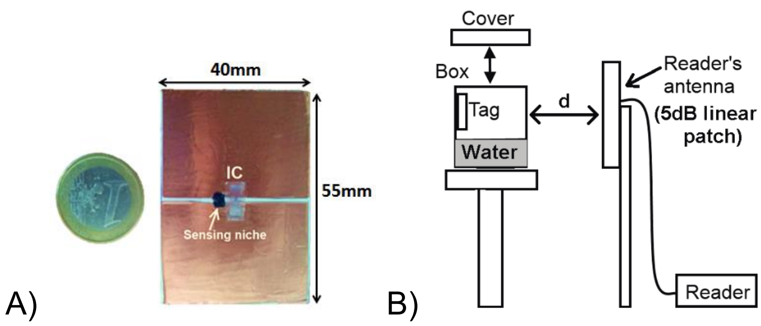
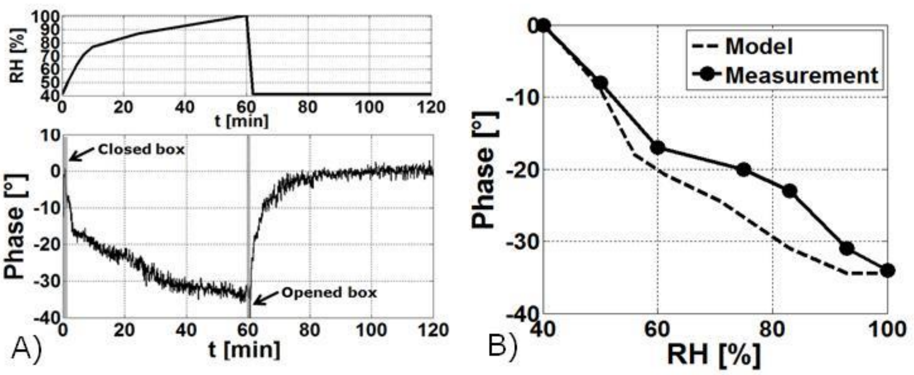


Fig. 4 A) Top view of the RFID tag humidity sensor prototype. The Pedot:PSS layer is the black spot labeled as "sensing niche". B) Measurement set-up.

Measurements were performed at fixed power (P_{in}=26 dBm) using a ThingMagic M6 reader, able to detect the phase at the frequency of 867 MHz. The sensor, doped by Pedot:PSS, was placed inside a closed plastic container, partially filled with water at a distance of 35cm from a linearly polarized patch antenna (Fig. 4 B). The container was first closed and the tag was exposed to increasing moisture for an hour up to saturation RH=100% (exposure time), then the container was opened dropping the relative humidity to ambient air RH=40% (recovery time).
Fig. 5 A) shows the measured variation of the signal's phase as normalized by the starting value for a single 2-hours cycle of exposure/recovery. The change of the response curve follows the exponential humidity profile up to saturation with a dynamic range of 35°. The recovery process toward the ambient humidity (RH=40%) lasted 1 hour, even if just 20 minutes revealed to be enough for the sensor to recover almost completely. The signal have been processed by a numeric low-pass FIR (Finite Impulse Response) filter of order N=48 in order to reduce the noise produced by the reader and the external environment, and achieving a minimum resolution of less than 2°.
A comparison between the calibration curves estimated by the circuit model and obtained by the measurement is reported in Fig. 5B) with a reasonable agreement for both dynamic ranges and sensitivities. The measured profile appear almost linear from 40% to 60% and 60% to 100% of relative humidity, therefore it is possible to extract the sensitivities of the device, defined as the phase difference generated by 1% change in the RH level, and calculable as

$$S_{\varphi} = \frac{|\Delta\varphi|}{|\Delta RH|} = \frac{\left|\varphi(RH_{high}) - \varphi(RH_{low})\right|}{\left|RH_{high} - RH_{low}\right|} \tag{7}$$

The sensitivity values for the phase based sensor are listed in Fig.5C and span from 0.4 to 0.8 deg/RH depending on the humidity level.



S[φ]	
RH_{low}-RH_{high}	[°/RH]
40% - 60%	0.85
60% - 100%	0.4

C)

Fig. 5 A) Measured variation of phase normalized for the initial value during one hour exposure to humidity and subsequent one hour recovery; B) Calibration curves calculated from the model and from experimental measurements of the RFID humidity sensor. C) Sensitivities [°/RH] of measured phase variation.

5. Conclusions

The processing of the phase of the modulated backscattered electromagnetic field from a chemically-doped RFID tag is suitable to produce monotonic information about the change of the environment. Preliminary experimentations have demonstrated that the dynamic response of the sensor is fully predictable by a circuital model allowing a fine control of the device's sensitivity.

6. References

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