Fingertip Self-tuning RFID Antennas for the Discrimination of Dielectric Objects

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***Abstract*—Self-tuning RFID antennas are based on a new family of multi-state microchips capable of automatically adapting an internal reactive network in order to maximize the power harvested by the attached antenna when boundary conditions change. This concept can be applied to develop a radio-frequency fingertip-augmented device (R-FAD) to be used as dielectric probe on a finger to discriminate different kinds of materials and their discontinuities. When the finger, provided with a self-tuning epidermal tag, comes in touch with an object, the modification of the input impedance of the tag, related to the object's material, can be retrieved by an interrogating reader placed on the wrist. Possible applications concern the aid to impaired people suffering from peripheral neuropathy or eyesight deficiency, but even the inclusion in a robotic prosthesis. The modeling and design and characterization of the epidermal self-tuning tag is here presented for the first time and the idea is corroborated by some experimental tests with a system prototype.**

***Index Terms*—Radio Frequency Identification, Multi-state Antennas, Finger Augmentation Devices.**

I. Introduction

The recently introduced new family [1], [2] of low-cost Radiofrequency Identification (RFID) chips in the UHF band is capable of dynamically adapting the internal input admittance, within a set of discrete states, at the purpose to balance possible changes of the antenna impedance during real operating conditions. While the original architecture was developed to make the tag performance as most insensitive to random boundary conditions, the changes in input impedance can be correlated with variations of external physical parameters, so that the self-tuning feature can be exploited for wireless sensing [3]. A comprehensive model of self-tuning tags as sensors in both linear and non-linear regime can be found in [4].

In this work, the unique features of self-tuning chips are exploited in combination with Epidermic Antennas [5] [6], made by thin and flexible substrates, to yield a new kind of *Finger Augmentation Device* (FAD) [7] capable of discriminating the permittivity of the touched objects.

FADs are electronic tools primarily worn on a finger aimed at expanding/recovering human senses based on the touch, thus providing a kind of sensorial *ultrability* also useful for an extremely efficient human-computer interface [8]. FADs can operate by using displays with cameras [9], haptic sensors [10], electro-tactile stimulators [11] or they can be used with RFID tags [12]. In particular, the first proof of concept of RFID-based FAD (named R-FAD) having sensing features has been recently presented in [13]. Such an R-FAD, involving bio-integrated antennas over the fingers, aimed to aid people suffering from Peripheral Neuropathy [14] and to restore the lost temperature feeling of their fingertips. Peripheral Neuropathy also provokes a loss or decrease of tactile sensitivity, which can cause problems in common tasks like finding a switch in the dark or sensing humidity of hairs after a shower. Problems in common tasks are also related to *visual impairment,* a pathological condition which hinders the visual impaired subject's capability to recognize objects and their materials and interact with them [15].

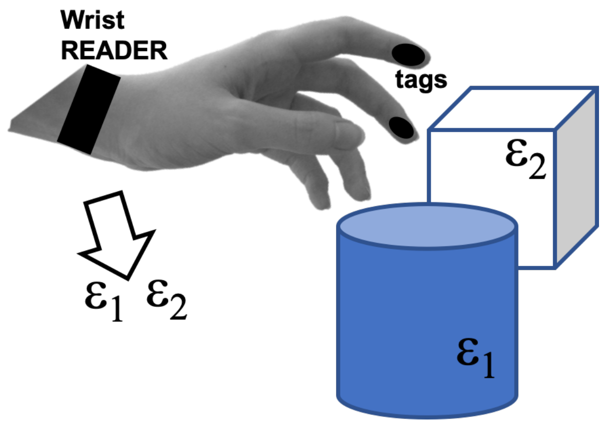

Figure 1. A pictorial concept of a Finger Augmented Device based on Self-tuning Epidermal Antennas attached on fingertips and on a wrist RFID interrogator for the sensing of the material of the touched objects.

When the finger provided with a self-tuning epidermal tag comes in touch with an object (Fig. 1), the modification of the input impedance of the tag, related to the object's material, can be retrieved by the interrogating reader placed on the wrist and correlated with the permittivity of the object.

Starting from the modeling of the response of self-tuning RFID tags, a first working prototype of epidermal R-FAD is here introduced and the leading idea is then corroborated by some preliminary realistic experimental tests.

II. Self-tuning Antennas and Dielectric Sensing

The architecture of self-tuning chips [1], [2] includes an adaptive internal switched network (Fig. 2) of N capacitors in parallel, with overall capacitance:

$$C_C(n) = C_{min} + nC_0 \tag{1}$$

Here, C_{min} is the baseline of the network, C_0 the incremental step and n is the number of connected capacitors adjusted by a logic in order to maximise the power that the tag's antenna delivers to the microchip. Accordingly, the equivalent susceptance $B_C(n) = \omega C_C(n)$ of the microchip automatically changes to compensate the deviation of the tag's admittance from the perfect matching condition:

$$|B_C(n) + B_T(\varepsilon)| = 0. \tag{2}$$

where ε is the permittivity of the object touched by the R-FAD and B_T is the susceptance seen by the microchip.

The integer parameter $0 \leq n(\varepsilon) \leq N$, hereafter referred to as *Sensor code*, is an indication of the retuning effort of the chip. Accordingly, the antenna susceptance can be matched by the chip only if it falls within the range:

$$-\omega C_{min} - NC_0 \leq B_T(\varepsilon) \leq -\omega C_{min} \tag{3}$$

Values of B_T that are smaller than the lower bound set in Eq. (3) will return a saturated sensor code to $n = N$, while values of B_T that are higher than the upper bound will return a saturated sensor code to $n = 0$.

Digital sensing capabilities can be achieved by exploiting the sensor code as a sensing metric for the permittivity since the susceptance of the antenna $B_T(\varepsilon)$ acts as a transducer between the permittivity ε and the sensor code *n:*

$$n(\varepsilon) = nint\left(-\frac{1}{C_0}(C_{min} + \frac{B_T(\varepsilon)}{\omega})\right) \tag{4}$$

with "*nint*" nearest integer or round function such that $nint(x)$ is the integer number closest to x.

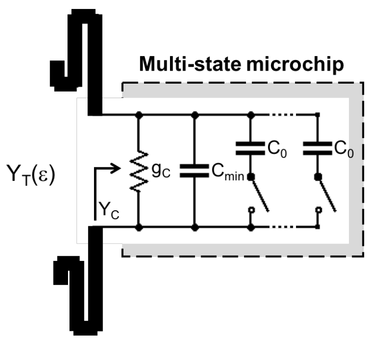

Figure 2. Schematic representation of the multi-state adjustable internal capacitive network of a self-tuning microchip.

III. Fingertip RFID tag

The considered self-tuning chip is the AXZON Magnus-S3 having power threshold $P_c = -16.6\ dBm$. According to the datasheet, the chip is capable of adjusting its internal tuning capacitance in the range $1.9 \leq C_C \leq 2.9\, pF$, while the nominal conductance is fixed to $g_C = 4.38 \times 10^{-4}\ S$. The sensor code spans in the range of $0 < n < 511$. From (1) the nominal network capacitances are accordingly estimated as $C_{min} = 1.9\, pF$ and $C_0 = 1\, pF/511$. The chip is also capable of temperature sensing in the range - 40 °C < T < 85 °C with resolution $\Delta T = \pm 0.5°C$.

The layout of the fingertip tag antenna is a T-match dipole conformal to the fingertip surface as in Fig.3. The size of the antenna was optimised by the help of numerical simulations (CST Microwave Studio) involving a homogeneous model of the hand (permittivity = 30, conductivity = 0.62 S/m, at frequency $f = 870\ MHz$) derived from [13].

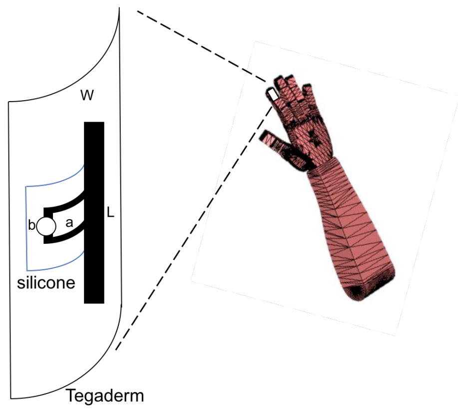

Figure 3. A conformal layout of a T-match dipole for application over the fingertip and numerical model of a homogeneous hand. Size of the antenna in [mm]: *a*=12, *b*=8, *L*=33, *w*=3.

The power transfer coefficient is computed in terms of admittance and by exploiting the self-tuning properties as follows:

$$\tau = \begin{cases} \frac{4 g_C g_T}{|g_C + g_T + j(B_T + \omega C_{min})|^2} & B_T > -\omega C_{min} \\ \frac{4 g_C g_T}{(g_C + g_T)^2} & elsewhere \\ \frac{4 g_C g_T}{|g_C + g_T + j(B_T + \omega(C_{min} + NC_0))|^2} & B_T < -\omega(C_{min} + NC_0) \end{cases} \tag{5}$$

Fig.4 shows the simulated input parameters and the realized gain of the fingertip tag versus the length L of the dipole. For all the considered values of L, the antenna susceptance falls inside the retuning range of the chip (shadowed band) while instead the admittance matching improves along with the size of the antenna. In order to preserve some comfort in the placement of the sensor over a fingertip, a tradeoff length *L*=33 mm is considered. Accordingly, the power transfer coefficient and the maximum realized gain, both evaluated at 870 MHz are $\tau(L = 33) = 0.7$, $\widetilde{G}(L = 33) = -14.4dB$, respectively. These values are in line with the typical gain of epidermal antennas, generally comprised between -15 dB and -10 dB [16].

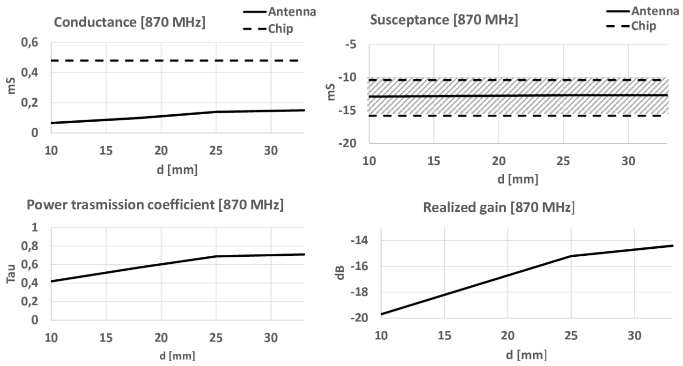

Figure 4. Simulated Input admittance of the fingertip dipole in Fig.3 vs. its length, at 870 MHz, with the indication of the value of the chip to be matched. The shadowed band in the susceptance diagram represents the useful retuning range of the self-tuning chip. The power transmission coefficient (evaluated as in (5)) and the resulting realized gain are also presented.

IV. Prototype and Characterization

A prototype of the fingerprint antenna was fabricated and tested. The antenna was made of aluminum over a PET substrate then carved around the T-match and fixed around the fingertip of a volunteer by means of a thin biocompatible breathable polyurethane film (thickness: 5μm) so that the chip is centered over the fingertip side (Fig.5).

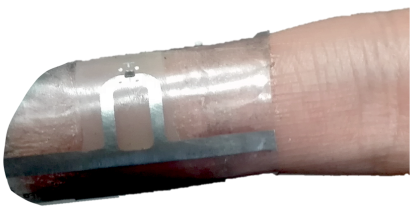

Figure 5. A prototype of the self-tuning tag attached to the fingertip by means of a 5 μm breathable polyurethane film and insulated in the middle by a 1 mm thick silicone layer.

In order to partly decouple the skin from the inner part of the antenna, where the currents are expected to be the highest, and hence to improve the efficiency of the tag, a small biocompatible silicone membrane (thickness 1 mm) was interposed between the chip region and the epidermis. The optimal size of this insulator was derived experimentally as shown next.

For the measurement purpose and for preliminary real-life tests, the tag was interrogated by a folded patch made of a closed-cell PVC foam-board substrate (Fig.6). The antenna was hence connected to the ThingMagic M5 reader to energize the tag.

Fig.7 resumes the turn-on power, i.e. the minimum power the reader has to transmit in order to force the tag responding, for some different size of the insulating silicone layer. The best performances are obtained when the silicone layer is placed only under the loop where the current strength is maximum. It is moreover worth noticing that the turn-on power is close to 21 dBm in the range 870-890 MHz. This value has to be compared with the maximum power produced by watch/keyfob -like portable readers that generally emit a maximum power of 23 - 27 dBm.

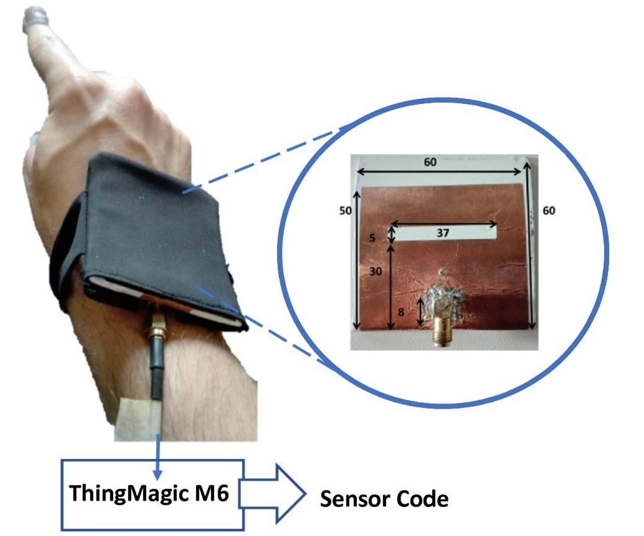

Figure 6. Interrogation set-up comprising a wrist-mounted folded patch antenna over a Closed-cell PVC foam-board substrate. The antenna is hence connected to a ThingMagic M6 reader for measurements.

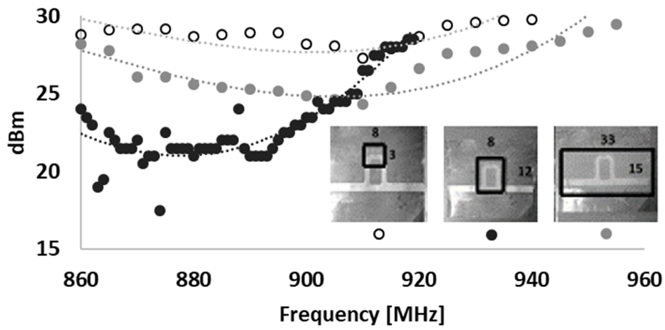

Figure 7. Turn-on power (the less is best) of several configurations of the fingertip antenna for different size of the insulating silicone layers. Continuous lines are for the least square interpolation of measured (circular markers) measured data.

V. Digital Response vs. Variable Boundary Conditions

The above self-tuning fingertip antenna was finally applied to the discrimination of some liquids and powders inside a PET bottle. The relative permittivity of the considered materials, as derived from public data, (Tab.I), spans between a few units (olive oil and sugar) up to more than 70 (wine and water) so that a significant contrast will be experimented.

Table I
PERMITTIVITY OF SOME MATERIALS USED FOR THE SENSING TESTS

materials	relative permittivity
Air	1
Olive Oil	3.1
Sugar	3.5
Salt	58
Ethyl alcohol	17
Milk	70.9
Wine	75.2
Water	78

The sensor code returned by the self-tuning antenna when the fingertip touched the bottles (averaged over five measurements, each lasting 15 seconds) are resumed in Fig. 8. The values are strongly correlated with the permittivity of the materials and in particular there is a sharp difference between the three sets {*milk, wine, water*}, {*ethyl alcohol*} and the lower-permittivity materials {*air, olive oil, sugar salts*}. The couples of materials {*wine, water*} and {*olive oil, sugar*} returned close values of sensor code, but are nonetheless distinguishable.

Several other tests with rubber layers of different thickness, plastic discontinuities, metal traces, wet objects and filling level of a bottle will be shown at the Conference.

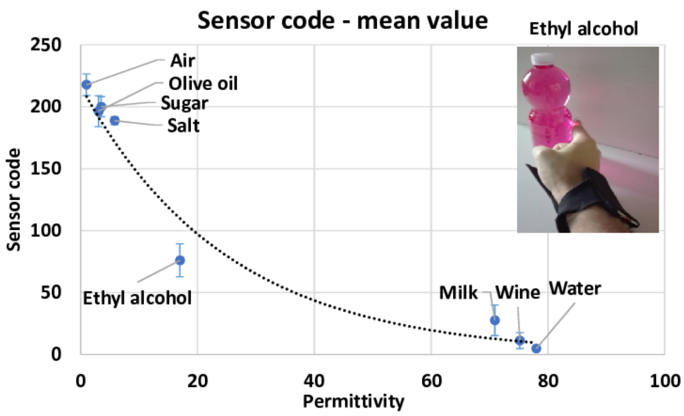

Figure 8. Sensor code returned at 868 MHz by the self-tuning fingertip antenna when touching a PET bottle filled with different liquids and powders.

VI. CONCLUSIONS

The proposed epidermal self-tuning tag for application over the fingertip demonstrated to be capable of providing information about the material touched by the sensorized finger. The dynamic range of the sensor code spanned in the experiments from 0 to 230 units which is not even half the declared range of the sensor. Accordingly, the resolution of the system could be improved by better equalizing the antenna response versus the dielectric change of the touched object throughout numerical optimization of the antenna layout in order to take advantage of the whole dynamic range of the sensor. At this purpose, a more accurate electromagnetic modeling of the near-field interaction between the self-tuning tag and the interrogating antenna is required. Preliminary results will be given at the conference.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

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