Experimentation and calibration of Near-Field UHF Epidermal Communication for emerging Tactile Internet

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***Abstract*—Tactile Internet (TI) is an emerging paradigm of the Internet of Things that exploits the Wireless Body Area Network wherein free-hand gestures are used as human/computer interface. The recently introduced Radiofrequency Augmentation Devices (R-FADs), which are assistive tools for sensory impaired people, can be considered also a promising enabler for TI. The core of R-FAD systems is a wrist reader and a fingertip sensor tag. An R-FAD for 'sensing' of dielectric objects can provide the users with feedback about the touched material. In this paper, we evaluate the variability of an R-FAD response on a personal basis. Results revealed that the user-specific variability can be mitigated by performing a calibration with respect to a high-permittivity material.**

***Index Terms*—Body-Area Internet of Things, Finger Augmentation Devices, Multi-state antennas, Radiofrequency Identification, Self-tuning IC, Tactile Internet**

I. INTRODUCTION

The recently introduced *Tactile Internet* paradigm consists of using hand gestures as human-computer interfaces to give input to a system and return an audio or video feedback to the user [1]. To avoid any sensorial dissonance between the input and the output and the resulting cybersickness [2], a very low reaction latency is required. The upcoming 5G is therefore considered an enabling technology for the Tactile Internet applications [3] ranging from healthcare to traffic, creating the idea of the Internet of Skills [4].

Electronic surfaces placed on the finger are usually referred to as Finger Augmentation Devices (FADs); these devices are designed with the aim to either restore lost senses or give the user a new sensorial ability, called *ultrability* [5]. For example, a FAD for the aid of multiple sclerosis patients is described in [6], whereas a fingertip screen was designed in [7]. The proposed FADs are mostly wired devices, hindering freehand gestures and thus resulting uncomfortable for the user. By using the Radiofrequency IDentification (RFID) paradigm and by exploiting fingertip-worn tags for sensing, the R-FAD systems were created. Pioneering R-FADs were designed and tested for restoring the thermal feeling [8] and for studying the cognitive neural remapping [9].

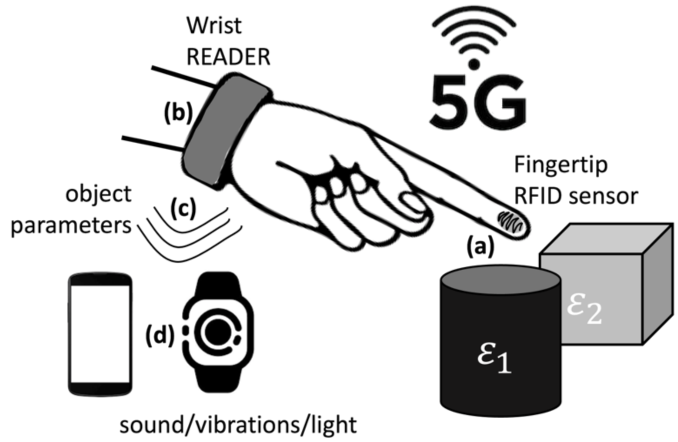


Figure 1. Concept of an R-FAD system for sensing of the dielectric constants in a 5G environment.

The major limitation of current R-FAD systems consists of the interruption of the wrist-finger communication link that occurs when the fingertip tag touches an object. This critical issue was recently mitigated by integrating self-tuning microchip transponders into the fingertip tag, such as the Impinj Monza R6 [10] and the AXZON Magnus-S3 [11]. These ICs are able to adjust their internal capacitance depending on the variable boundary conditions [12], thus providing the tag with some insensitivity to the dielectric nature of proximal/contacting objects. Self-tuning tags for sensing temperature [13] and water content [14] have already been successfully tested. In particular, the use of an R-FAD system exploiting the self-tuning for sensing the dielectric permittivity (Fig. 1) of the touched object was proposed in [15], with the aim to aid visually and sensory impaired people through a new ultrability. Following the proof-of-concept in [15], this paper investigates the variability of the response of the R-FAD system with self-tuning tags on an individual basis, to introduce a calibration procedure aimed at providing useful and robust data for the automatic recognition of touched objects.

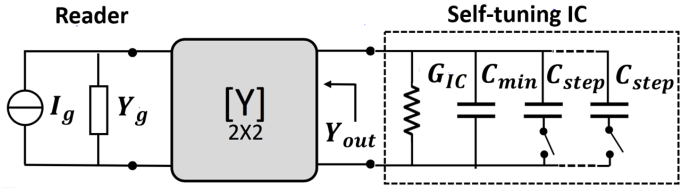


Figure 2. two-port network model of the fingertip-reader link. The self-tuning IC is accounted for by a variable capacitance whose value is a dynamic function of the susceptance B_{out} seen from the IC terminal.

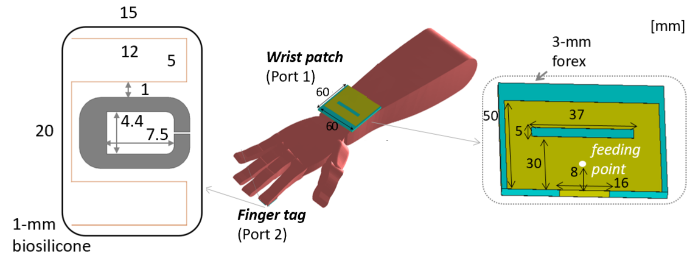


Figure 3. Components of the R-FAD under test: 1) fingertip tag consisting of a wire dipole with loop match and 2) wrist reader antenna in the form of a folded patch.

II. Self-tuning Antennas and Two-Port Model

Integrated Circuit (IC) transponders provided with the self-tuning feature have an analog front-end with a variable capacitance, which dynamically changes its value to maximize the power collected by the circuit [16]. The radiofrequency equivalent input admittance of the IC is $Y_{IC} = G_{IC} + j\omega C_{IC}$, thus it can be modelled as a conductance in parallel to a switchable ladder network of equal capacitors. The overall microchip capacitance therefore is:

$$C_{IC}(n) = C_{min} + nC_{step} \tag{1}$$

where C_{min} is the baseline of the network, C_{step} is the incremental capacitance step and $N_{min} \leq n \leq N_{max}$ is the *Sensor Code* (SC), an integer number accounting for the re-tuning quantization. Denoting with $Y_A(\varepsilon) = G_A(\varepsilon) + jB_A(\varepsilon)$ the admittance of the tag's antenna when a tag contacts a dielectric material with permittivity ε, the equivalent capacitance of the self-tuning IC $C_{IC}(n)$ adjusts automatically to compensate the susceptance mismatch with the antenna so that the following self-tuning matching condition is enforced:

$$|\omega C_{IC}(n) + B_A(\varepsilon)| = 0 \tag{2}$$

According to the above model, the self-tuning is expected to stabilize the antenna performances while touching different materials by compensating the mismatch between the antenna's susceptance and the IC's one. Noticeably, the self-tuning does not compensate for the eventual conductance mismatch between the antenna and the IC caused by the conductivity of the contacted material. The SC is inversely proportional to the permittivity of the touched object as demonstrated in [15], thus it can be exploited for sensing applications. Unlike the analog sensing that is based on processing the amplitude and phase of the backscattered signal [17], the Sensor Code is immune to the propagation noise and artefacts [18] since it is a digital metric.

In UHF R-FAD systems the antennas of the wrist reader and the fingertip tag are placed at a close distance so that a two-port network is used to model the coupling effects. The two-port model in Fig. 2 accounts for both the electromagnetic coupling and the self-tuning, and it is based on the Norton equivalent circuit involving the Admittance matrix $[Y]$.

The Transducer Power Gain (G_T) is used as the performance metric of the system:

$$G_T = \frac{P_{R \to T}}{P_{av,R}} \tag{3}$$

where $P_{R \to T}$ is the power delivered by the reader to the chip while $P_{av,R}$ is the available power emitted by the reader generator. Assuming a reciprocal network, and following a dual approach than in [19], it is possible to demonstrate that the input admittance Y_{out} seen by the IC port is:

$$Y_{out} = G_{out} + jB_{out} = Y_{22} - \frac{Y_{12}^2}{Y_{11} + Y_g} \tag{4}$$

where the reader is placed at port 1, the IC at port 2 and $Y_g = G_g + jB_g$ is the admittance of the reader generator. Therefore the input susceptance seen by the IC port is:

$$B_{out}(\varepsilon) = Im\left[Y_{22}(\varepsilon) - \frac{Y_{12}^2(\varepsilon)}{Y_{11}(\varepsilon) + Y_g}\right] \tag{5}$$

It is possible to demonstrate that the transducer power gain expression can be hence written as:

$$G_T = \frac{4G_g G_{IC} |Y_{12}|^2}{\left|(Y_{11} + Y_g)(Y_{22} + Y_{IC}) - Y_{12}^2\right|^2} \tag{6}$$

where $Y_{IC} = G_{IC} + j\omega C_{IC}(n)$ follows the self-tuning matching condition.

III. The R-FAD system

The considered R-FAD platform (Fig. 3) comprises: a patch-like wrist interrogator and a soft fingertip meandered dipole made by thin wire and coupled to a small excitation loop which embeds the self-tuning chip (Magnus-S3 IC from Axzon [11]). The manufactured prototypes are shown in Fig. 4. Fig. 5 reports the comparison of the simulated[1] and measured transducer power gain. Measurements were performed on a female volunteer wearing the R-FAD system in three reference hand gestures: open hand, pointing and prehension. A 4 dB difference between simulation and measurements is achieved at 870 MHz, mainly due to the differences between the real hand of the volunteer and the simplified numerical hand model in Fig.

[1]Numerical simulations by CST Microwave Studio® 2019

Figure 4. Prototypes of the wrist antenna and of the soft fingertip tag.

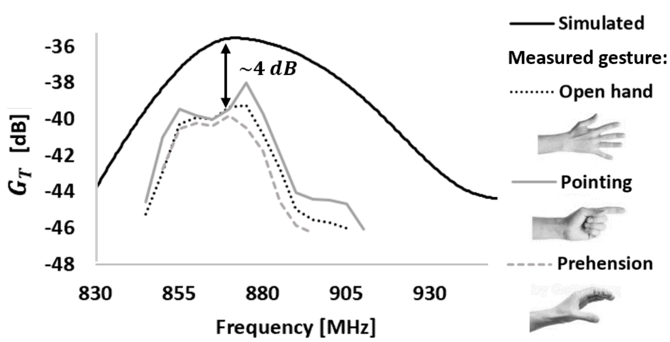


Figure 5. The simulated and measured transducer power gain of the R-FAD system for three different hand gestures.

3. The different hand gestures have instead negligible effects on the performance parameter.

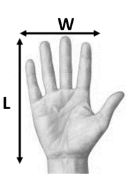
IV. Set up and measurements

Four volunteers tested the sensing capabilities of the system: two females and two males having different hand sizes (Tab. I). They were asked to wear the system and touch three bottles made of polyethylene terephthalate (thickness: 0.3 mm) filled with liquids having different permittivities (reported in Tab. II).

The volunteers performed the pointing (Fig. 6.a) and prehension (Fig. 6.b) gestures firstly in a reference air condition (i.e. without touching any object) and then and then by touching three bottles (Fig. 6.c). The returned Sensor Codes[2] (averaged over five measurements per user, each lasting 3

[2]The Magnus-S3 IC returns SC values between 0 and 511.

Table I
Volunteers' hand dimensions.



Volunteer	Hand length (L)	Hand width (W)
Female 1	17 cm	7 cm
Female 2	15,5 cm	6 cm
Male 1	18 cm	7 cm
Male 2	19,5 cm	7,5 cm

Table II
Dielectric properties of the liquid selected for testing ($f = 870$ MHz).

Material	Dielectric constant ε_r	Dielectric loss factor ε''
Air (no bottle)	1	0
Olive oil [20]	3	0.18
Ethyl alcohol (90%) [21]	17	10
Vinegar [22]	79	13

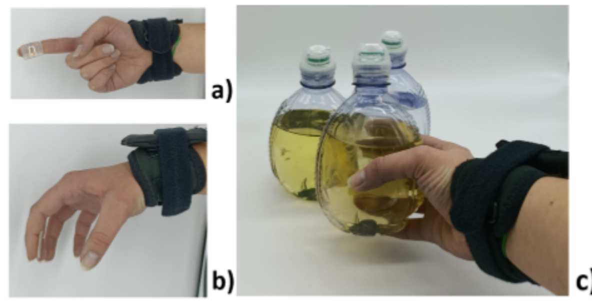


Figure 6. Measurement setup for testing. a) Pointing and b) prehension gestures. c) Bottles filled with ethyl alcohol, olive oil and vinegar touched by a volunteer performing the prehension gesture.

seconds) are reported in the bar plot in Fig. 7. The SC(air) measured in the reference air condition are rather similar (263 ± 7) despite different users and gestures, while the SCs for the liquids appear very sensitive to both the specific user and gesture.

User variability can be reduced by calibration. The SCs measured were normalized by subtracting the average SC(vinegar) value measured on the same user and gesture. The resulting Differential Sensor Code (ΔSC) metric greatly reduces the interpersonal variability (Fig. 8) while maintaining significant differences for each material through the volunteers. It is worth noticing that the materials can be recognized even in the most critical situations when considering only the raw SC values would lead to ambiguities, e.g. the raw SC(alcohol) of Female 1 is equal to the average raw SC(vinegar) of Female 2 (see Fig. 7). Moreover, the returned ΔSC while touching the alcohol-filled bottle is very similar in both the prehension and pointing case.

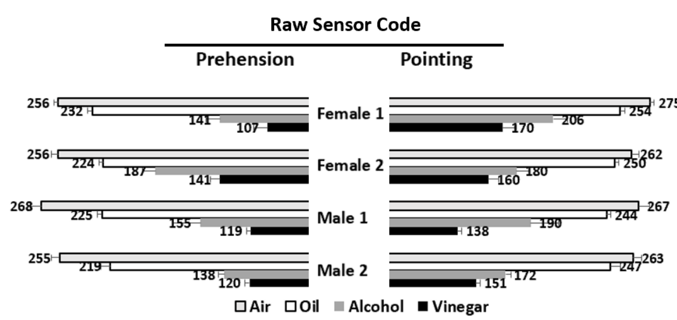


Figure 7. Raw measured Sensor Codes over four volunteers and two different gestures performed while touching different materials.

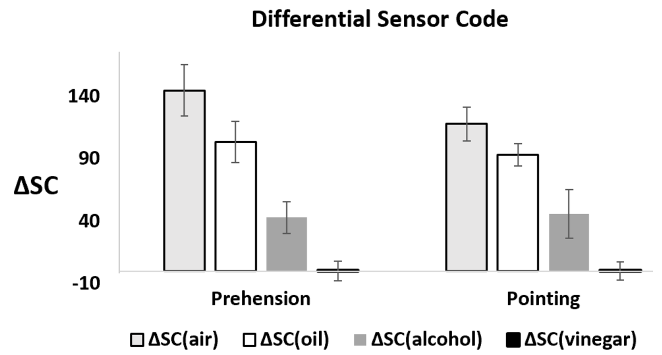


Figure 8. Average and Standard Deviation of measured Differential Sensor Code over four volunteers and two different gestures performed while touching different materials. The average ΔSC of vinegar is null.

V. Conclusions

An R-FAD system for the discrimination of dielectric objects was introduced and experimentally evaluated over four different subjects for the recognition of three liquids having different dielectric properties. The Sensor Code metric revealed rather sensitive to both the user and to the gesture performed while touching the bottle. However, the inter-user variability was greatly reduced by normalizing the raw measured Sensor Code by the data obtained while touching the highest-permittivity material. Future work can improve the metric robustness by involving additional electromagnetic indicators such as the power collected by the chip and the phase of the backscattered field.

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