Multi-Channel Radiofrequency Finger Augmentation Device for Tactile Internet

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Abstract

The Tactile Internet (TI) aims to enhance human-to-machine interactions by transmitting the human senses through the internet. Promising candidates to enable TI applications in the short term are the Radiofrequency Finger Augmentation Devices (R-FADs), hand-worn epidermal RFID (Radiofrequency Identification) systems. R-FADs were employed to recover the thermal feeling and discriminate dielectric materials. Preliminary experiments only considered single-channel R-FADs, whereas multi-channel systems with multiple tags could more reliably sense and communicate with the reader. In this work, a multi-tag R-FAD is for the first time manufactured and tested. The five tags’ combined response, named digital fingerprint, allows for more reliable discrimination of the tested materials.

1 Introduction

The Tactile Internet (TI) is an emerging technology that aims to revolutionize human-to-machine interaction [1] by spreading the human senses through the Internet. TI is expected to be boosted by 5G mobile communication networks [2] which can handle massive data traffic with extremely low end-to-end latencies so that the user is not affected by cybersickness [3]. An interesting application is the recovery of damaged sense, but the implementation of new kinds of perception denoted as sensorial ultrability [4], is possible, too. The enabling technology for TI is that of Finger Augmentation Devices (FADs) [4] based on Epidermal Electronics. Moreover, waiting for 5G technology to become more mature, UHF Radiofrequency Identification (RFID) can be exploited in the short term to establish communication links through backscattering modulation, avoiding batteries on the tags. Using Epidermal Electronics, soft and stretchable devices can be fabricated for application on the fingertips so that the user’s natural gestures are not hindered.

Recently, Radiofrequency FADs [5] (hereafter denoted as R-FADs) were proposed for the restoration of peripheral thermal feeling in impaired people [6]. R-FADs were then empowered by including a new family of ICs (Integrated Circuits) having auto-tune capability. Namely, they can automatically modify their internal impedance to make the matching to the hosting tag antenna nearly insensitive to changes of local boundary conditions. A constrained method for designing these devices was proposed in [7] and then applied to recognize some liquids filling a bottle, with interesting applications to aid blind people. In all cases, just a single fingertip was sensorized and, hence, the real potentiality of this framework is still mostly under-used.

This paper explores, for the first time, a multi-channel R-FAD, wherein all the five fingertips are simultaneously sensorized, so that richer information is available to recognize the touched objects. Having recalled the rationale for dielectric sensing with auto-tuning ICs, an experimental setup comprising stretchable fingertip antennas is applied in a test campaign involving volunteers touching different materials. The goal is to evaluate the inter-user variability of the collected data, and, most importantly, identify the digital contrast of the measurements with respect to a single-finger sensing.

2 Rationale of Dielectric Sensing by Auto-tuning chips

The core of an auto-tuning RFID IC [7] can be modelled as an adaptive internal network of parallel capacitors, whose total capacitance depends on the number s of activated components:

\[ C_{IC} (s) = C_{min} + sC_s \]  

(1)

where \( C_{min} \) and \( C_s \) are specific parameters of the IC. The resulting index saturates outside the range \( N_{min} \leq s \leq N_{max} \), where \( N_{min} \) and \( N_{max} \) depends on the implementation of the IC. The equivalent susceptance
of the microchip is automatically modified to compensate for variations in the susceptance of the tag, to make the antenna-IC a resonant system [8]:

\[
|B_{IC}(s) + B_A(\varepsilon)| = 0. \tag{2}
\]

\(B_A(\varepsilon)\) is the input susceptance of the tag antenna when it is in touch with the object of dielectric effective permittivity \(\varepsilon\). The parameter \(s\), hereafter denoted as sensor code, is returned by the IC following a standard RFID query. It can be considered a metric that indirectly carries information about the touched material through the relationship:

\[
s(\varepsilon) = nint \left( -\frac{1}{C_s} \left( C_{IC} (N_{\min}) + \frac{B_A(\varepsilon)}{\omega} \right) \right) \tag{3}
\]

where “nint” identify the nearest integer number. By considering the five sensors on the fingers the set \(F(\varepsilon) = \{s_1(\varepsilon), \ldots s_5(\varepsilon)\}\) is the digital fingerprint of the touch that is captured the R-FAD system. By processing \(F(\varepsilon)\), a recognition of the touched material can be achieved.

2 Experimental Setup

Each fingertip tag consists of a T-match aluminum dipole connected to the Magnus chip-S3 IC (by RFMicron). To obtain a flexible and stretchable device (Fig. 2.a), the dipole is encapsulated by two layers of Ecoflex™ 00-30 (by Smooth On). To guarantee a stable adherence to the skin, a further layer of Silbione (by Elkem Silicones) is then deposited on the side that has to be in direct touch with the fingertip.

The resulting prototype is bio-compatible, soft, gently following the finger’s natural bending and can be detached and attached several times, after cleaning. The readers’ antenna is a folded patch (from [8]) made of a closed-cell PVC foam-board substrate (Fig. 2.d), that is placed on the back of the hand. Fig. 3.a shows the numerically simulated (by CST Microwave Studio 2019) electric field over a homogeneous hand phantom [7] when the reader antenna is active. The central three fingers (II, III and IV) are well exposed to the antenna radiations, whereas a less robust link with the thumb is expected. The field produced by each fingertip tag (considered in transmitting mode) is mostly local, and, accordingly, the five tags are expected to be weakly electromagnetic coupled.

![Image](image_url)

**Figure 3.** Map of the near electric field on the skin when a single antenna is sourced by 1 W power: (a) electric field radiated by the patch, and (b) by each single fingertip tag (assumed in transmitting mode).

**Table 1.** Size of volunteers’ hands

<table>
<thead>
<tr>
<th>Volunteer</th>
<th>a [cm]</th>
<th>b [cm]</th>
<th>c [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female 1</td>
<td>7.8</td>
<td>18.0</td>
<td>8.7</td>
</tr>
<tr>
<td>Female 2</td>
<td>7.5</td>
<td>16.2</td>
<td>8.3</td>
</tr>
<tr>
<td>Male 1</td>
<td>8.0</td>
<td>19.5</td>
<td>9.5</td>
</tr>
<tr>
<td>Male 2</td>
<td>9.0</td>
<td>18.5</td>
<td>8.2</td>
</tr>
</tbody>
</table>
The communication performance of the multi-channel system was measured by the help of four volunteers (hand size in Tab. 1) wearing the epidermal tags in open hand configuration in air. The interrogating reader was a ThingMagic M5. The considered performance metric is the turn-on power \( P_{\text{on},n} \), namely the minimum power the reader as to emit to have the \( n \)-th fingertip tag responding.

Fig. 4 resumes the measurements at the European UHF RFID frequency (868 MHz) when all the tags were simultaneously worn. The inter-user variability is about ±2.5 dBm.

As expected from the electromagnetic simulations, the tag on the thumb is the most problematic one concerning the activation, compared to the other fingers for all the users. Even in the worst case (red circle), all the tags will require less than 25 dBm. This value is compatible with hand-held readers with a size similar to watches or key fobs so that integration with the interrogating antenna is possible.

3 Measurements

To quantify the sensing performance, volunteers were asked to touch three bottles (6.5 cm diameter, 0.3 mm thickness) made of polyethylene terephthalate filled with liquids having different relative dielectric permittivity: olive oil \((\varepsilon_1 = 3)\), ethyl alcohol \((\varepsilon_2 = 17)\) and deionized water \((\varepsilon_3 = 78)\) (permittivities in [7, 9]). The volunteers performed an open-hand gesture, firstly in the air (i.e. hands open, without touching any object) and then a prehension gesture by touching the bottles. The measured sensor codes are averaged over ten samples. Then, a calibration, with respect to the bottle-less case, is applied to remove the individual baseline [9]. Consequently, the digital fingerprint is referred to differential sensor codes so that

\[
F(\varepsilon_m) = \{ s_1(\varepsilon_m) - s_1(1), \ldots s_5(\varepsilon_m) - s_5(1) \} \tag{2}
\]

where \( s_n(1) \) is the sensor code returned by the \( n \)-th sensorized finger “in the air”, i.e. in the absence of the object. Radar-plots of the digital fingerprints are shown in Fig. 5, where some missing data from non-responding tags are replaced by the average on the other responding ones. Polygons corresponding to the different materials are well discriminated. In particular, their areas are reported in Fig. 6.

To better quantify the advantage of using all the fingers, Fig. 7 shows a comparison among sensor codes in case of multi-channel systems, averaged over the five fingers, with the values of a single-channel (index finger)
configuration. The digital contrasts, i.e., the gaps of the sensor codes between different materials, are shaper in the case of multi-channel measurements. Accordingly, the recognition of the materials is expected to be more accurate. In all cases, the standard deviation (caused by the inter-user variability) is modest and just of the order of few units, and hence the measurement can be considered robust.

Figure 6. Areas of the digital fingerprints in Fig. 5 normalized by the maximum value.

Figure 7. Average and standard deviation of measured differential sensor codes. (a) Single tag over the index finger, and (b) case of the multi-channel system, where the five fingers’ values are averaged.

4 Conclusions

A multi-channel R-FAD system, based on soft and stretching epidermal RFID and auto-tune IC sensors, has been presented and preliminary experimented. Tests over four volunteers demonstrate that in all cases the five sensorized fingers can be interrogated by a back-hand patch sourced by not more than 25 dBm that is compatible with low-cost battery-assisted readers. When applied to the sensing of bottles filled with a liquid of different materials, the multi-channel systems returned data with a higher digital contrast w.r.t. a single channel arrangement. This feature will be beneficial for robust classification of touched materials. A more comprehensive experimental campaign is in progress, and additional results, also exploiting other metrics, will be presented at the conference.

5 References


