Near-field modeling of Self-tuning Antennas for the Tactile Internet

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Abstract

Tactile Internet (TI) is the new frontier of the Internet of Things that is based on free-hand gestures as a human/computer interface. A promising enabler for TI is the recently introduced Radiofrequency Finger Augmentation Device (R-FAD) family, assistive technology for the recovery of lost or damaged senses. The R-FAD core comprises a wrist reader coupled in near-field with a fingertip sensor tag. To prevent the interruption of the wrist-finger link during the touch of objects, self-tuning microchips must be used since they are capable to adapt their internal impedance and preserve the communication. A unitary electromagnetic/electric model is here proposed to address the double specificity of R-FAD devices for TI, namely the Near-Field interaction among the antennas, and the dynamic behavior of the IC. The model is based on a two-port network and is suitable for the application to the constrained design of robust communication links.

1 Introduction

The *Tactile Internet* paradigm consists in using hand gesture as a human-computer interface, taking benefit of the low latency of the 5G networks [1]. Tactile Internet applications can exploit the research on Finger Augmentation Devices (FADs), which are electronic surfaces worn on the fingers with the aim to recover lost human senses or empower the user with new ones, thus yielding a sensorial *ultrability* [2]. Several different FAD were proposed, but their main limitation is that they are wired devices, hindering free hand gesture and being discomfortable for the user. In order to overcome these limits, FADs were recently combined with RadioFrequency IDentification (RFID) creating wireless systems called Radiofrequency FAD (R-FAD) in the UHF band (860-960 MHz), composed by a wrist-worn reader and a sensing tag worn on the fingertip (Fig. 1). An R-FAD system was recently used for studying the cognitive neural remapping [3]. However, when the fingertip sensor touches an object a relevant impedance mismatch happens between the antenna and the electronic circuit, thus the communication link is interrupted. This problem can be solved by self-tuning microchips which are capable of varying their internal capacitance value to adapt to the changed boundary conditions [4], giving also the user a digital number, called *sensor code* (SC), which is

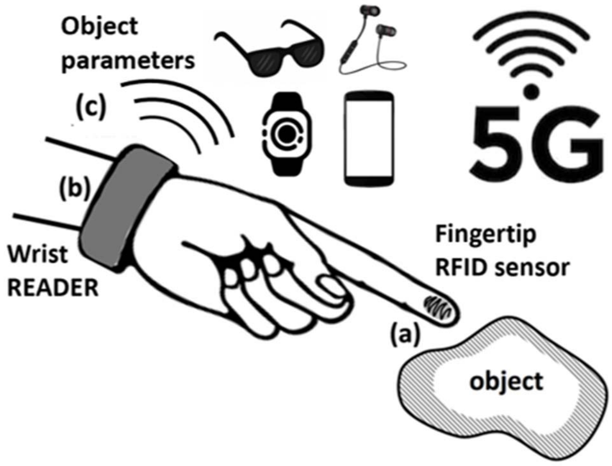

Figure 1. Sketch of an R-FAD system comprising a fingertip RFID sensor tag (a) which is coupled in near-field with a wrist-worn reader (b) and returns some measured parameters of the touched object via backscattering modulation. The object parameters (c) are then sent by the wrist reader to a body-worn device (smartphone, earphones, smartwatch or smart glasses) via 5G, ensuring the low latency required by Tactile Internet.

proportional to the retuning effort of the chip. The SC was exploited for sensing of currents [5] and dielectric constants [6]. As the transmitting antenna and the tag are placed at a very close distance, sharing also the same hosting medium, e.g. the wrist and the hand, their electromagnetic interaction takes place in the Near-Field. Accordingly the design, for instance of the tag, cannot be disjoined by the transmitting antenna. This paper, therefore, presents an electromagnetic model for RFID coupled system in the UHF band also able to account for the dynamic input impedance of the chip.

2 Self-tuning antennas and two-port model

Self-tuning ICs include an analog front end with a voltage-controlled capacitor which is automatically adjusted to maximize the incoming radiofrequency power collected by the chip itself [7]. Denoting with $Y_{IC} = G_{IC} + j\omega C_{IC}$ the radiofrequency equivalent admittance of the microchip, the tuning mechanism can be modeled as a resistance in parallel to a variable capacitance, which in turn can be

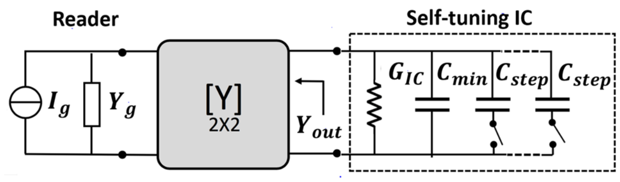

Figure 2. Two-port network model of the fingertip-reader link where the self-tuning IC is modeled using a variable capacitance whose value is a dynamic function of the susceptance B_{out} seen from the IC terminal.

seen as a switchable ladder network of equal capacitors with overall capacitance:

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

being C_{min} the baseline of the network and C_{step} the incremental step. The integer number $N_{min} \leq n \leq N_{max}$ accounts for the quantization of the actual IC capacitor. Being $Y_A(\varepsilon) = G_A(\varepsilon) + jB_A(\varepsilon)$ the admittance of the tag contacting a dielectric with permittivity ε, the equivalent capacitance $C_{IC}(n)$ is automatically adjusted to compensate any difference with $(-B_A(\varepsilon))$ so that the following self-tuning impedance matching equation holds:

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

Saturation of the variable capacitor is also accounted for, so that $C(n<N_{min}) = C_C(N_{min})$ and $C_C(n>N_{max}) = C_C(N_{max})$. The self-tuning is expected to stabilize the antenna performances over different types of touched objects. The reader-tag interaction in the Near-Field is here modelled by means of a two-port network (Fig. 2) based on the Norton equivalent model with Admittance matrix [Y]. The Transducer Power Gain (G_T) [8] is used as the performance metric of the system, according to the formula:

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

where $P_{R\rightarrow T}$ is the power delivered by the reader to the chip whereas $P_{av,R}$ is the available power of the reader's generator. By resorting to the Π-equivalent topology of the network and by following an approach dual to [8]. the input admittance Y_{out} seen by the IC port can be expressed as:

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

where $Y_g = G_g + jB_g$ is the admittance of the reader. According to the model in Fig. 2, the susceptance to insert in eq. (2) is $B_{out}(\varepsilon)$, which can be derived from the network admittances Y_{ij} as follows:

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

Accordingly, the transducer power gain becomes:

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

By exploiting the self-tuning behavior of the IC in (2), the transducer power gain of the link, accounting for all the electromagnetic interactions, as well as for the dynamic impedance of the chip, can be finally derived from (1), (2) and (6) as:

$$G_T = \begin{cases} \dfrac{4G_g G_{IC}|Y_{12}|^2}{\left|(Y_{11} + Y_g)(Y_{22} + G_{IC} + j\omega C_{IC}(N_{min})) - Y_{12}^2\right|^2} \\ if\ B_{out} > -\omega C_{IC}(N_{min}) \\ \dfrac{4G_g G_{IC}|Y_{12}|^2}{\left|(Y_{11} + Y_g)(Y_{22} + G_{IC} - jB_{out}) - Y_{12}^2\right|^2} \\ if\ -\omega C_{IC}(N_{max}) < B_{out} < -\omega C_{IC}(N_{min}) \\ \dfrac{4G_g G_{IC}|Y_{12}|^2}{\left|(Y_{11} + Y_g)(Y_{22} + G_{IC} + j\omega C_{IC}(N_{max})) - Y_{12}^2\right|^2} \\ if\ B_{out} < -\omega C_{IC}(N_{max}) \end{cases} \tag{7}$$

For practical applications, the admittance matrix [$Y(ij)$] can be numerically evaluated by an electromagnetic solver while the overall link budget, namely the power $P_{R\rightarrow T} = G_T P_{av,R}$, can be derived by means of (7) for the specific tag-chip measured.

3 Conclusions

We introduced here a unitary model of Near-Field link involving also microchips with variable impedance. This formulation can be applied to set-up a constrained design of the tag so that the transducer power gain remains constant when the tag (fingertip antenna) is placed in touch with different materials. An example of constrained design for R-FAD will be shown at the conference, together with an experimental validation with some volunteers.

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