Performances of a 3.6 GHz Epidermal Loop for Future 5G-RFID Communications

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***Abstract*—This paper explores, through simulations and preliminary experiments, the feasibility of a 5G-RFID link for a backscattering epidermal sensing architecture integrated within the 5G network. It demonstrates how a 3.6 GHz loop tag could provide the same read distance (one meter) of three-times larger UHF counterparts. The proposed loop is compliant with regulations on electromagnetic exposure and can theoretically achieve data rates up to 0.52 Gbps.**

***Index Terms*—5G, RFID, backscattering, epidermal antennas, microwave.**

I. Introduction

Biomedical digital and hardware sensors are essential for supporting prevention of health risks, self-empowerment of patients, diagnostics, treatments, and independent living in a world of ever-expanding and aging population. New wireless flexible and stretchable sensors have been recently proposed for collecting physical and chemical parameters (temperature, sweat, pH, breath, pressure) directly from the body. Low-cost, comfortable and battery-less epidermal configurations are only possible with passive Radiofrequency Identification (RFID) whose drawbacks are the short ranges, the narrow bandwidth, and their limited use due to the need of an RFID reader. A convergence of body network RFIDs within the forthcoming wide-band, high-speed Fifth generation (5G) wireless communication systems operating at microwave and mmWave frequencies should be encouraged to develop a 5G-RFID network embedded within the 5G infrastructure.

It has been demonstrated [1] that epidermal dipoles onto the skin and operating at either microwave or mmWave frequencies provide higher gains and higher radiation efficiencies than their UHF counterparts. Epidermal loops keep the same properties of dipoles with the added advantage of having a smaller footprint. This article discusses the radiation performances of a 3.6 GHz epidermal loop and verifies the feasibility of a 5G-RFID body wireless network in terms of reading ranges, data rates, and electromagnetic exposure.

II. Rationale

Currently, the chip sensitivity, p_t, of a passive UHF-RFID tag limits the communication range in the forward link whose power budget is described by the Friis equation[1]:

$$P_{R\to T} = P_{in} G_R G_T \left(\frac{c}{4\pi f r}\right)^2, \tag{1}$$

[1]Assuming co-polarized and perfectly matched reader and tag antennas.

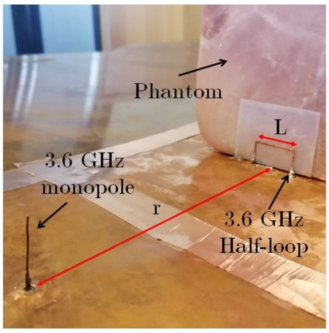

Fig. 1. Experimental setup for measuring the gain of the 3.6 GHz epidermal half-loop when attached onto a roasted pork phantom.

where $P_{R\to T}$ is the power reaching the chip of the tag, P_{in} is the transmitted power, G_R and G_T are the gains of the reader and the tag, respectively, c is the speed of light, f is the operation frequency, and r is the distance between the reader and the tag. The maximum read range is achieved when enough power reaches the tag IC to wake up its circuitry, i.e.: when $P_{R\to T} = p_t$. With this assumption, and when fixing the input power P_{in}, the maximum read range becomes:

$$r_{max} = \sqrt{\frac{P_{in} G_R G_T}{p_t}} \left(\frac{c}{4\pi f}\right). \tag{2}$$

Therefore, designing an epidermal RFID system to operate at microwave frequencies might sound counter-intuitive since higher values of f increase the path-losses, causing a reduction in the maximum achievable range r_{max}. Nonetheless, at frequencies higher than UHF, the outer skin acts as a reflector that reduces the amount of power delivered into the inner layers and providing higher gains to epidermal antennas. To verify this claim, numerical analyses in CST Microwave Studio and experimentation have been performed and hereafter discussed.

III. The 3.6 GHz Epidermal Loop

The radiation performances of the 3.6 GHz epidermal loop tag (160 μm trace width and increasing size L) have been simulated when placed at a distance of 0.25 mm from a flat 3-layered model of the human body consisting of skin (1 mm, $\epsilon_r = 36.92$, and $\sigma = 2.08\ \frac{S}{m}$), fat (3 mm, $\epsilon_r = 5.16$, and $\sigma = 0.16\ \frac{S}{m}$) and muscle (31 mm, $\epsilon_r = 51.32$, and $\sigma = 2.65\ \frac{S}{m}$) [2]. The numerical results have been verified through the experimental setup in Fig. 1 using a cubic phantom made by roasted pork. Planar half-loops (trace width: 1 mm) of different

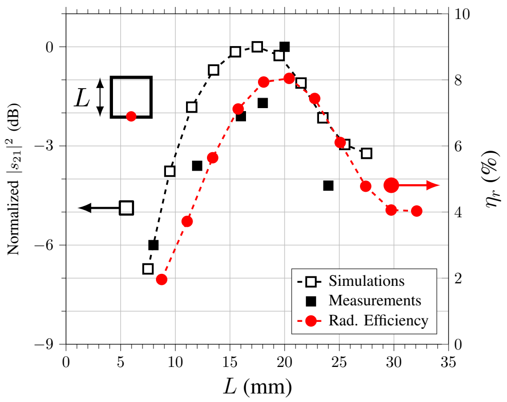

Fig. 2. Comparison between measured and simulated normalized gains of the 3.6 GHz epidermal loop and radiation efficiencies η_r as function of L. Inset: in-scale view of the 3.6 GHz loop, size: 17.5 x 17.5 mm^2.

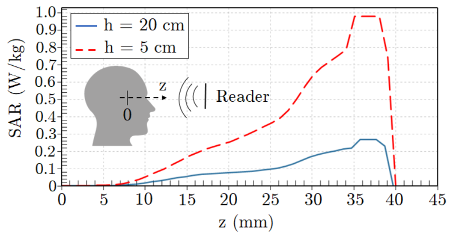

Fig. 3. SAR distributions from a source emitting 4 W EIRP at 5 and 20 cm away from the face. Results are below the FCC requirements of 1.6 $\frac{W}{kg}$ averaged over 1 g of tissue.

length L were manufactured over PET substrate (thickness t = 0.135 mm) with adhesive copper that was carved out by a two-axis cutter. Samples were mounted on a ground plane and vertically attached onto the phantom. The gains were indirectly measured through a test monopole ($\frac{L}{2}$ = 20 mm) placed 13 cm away from the half-loop under test. The s_{21} scattering parameters were then measured by a VNA (HP 8517A) upon calibration. Results of normalized $|s_{21}|^2$ (proportional to the normalized antenna gains) are plotted in Fig. 2 and compared with the corresponding simulations. In spite of a small shift, due to the manufacturing imperfections and, above all, to the approximate resemblance between simulated and real phantoms, the existence of an optimal size is reasonably verified. Coherently with [3], there exists an optimal length, L_{opt}, of 17.5 mm where both the gain and the radiation efficiency are maximum (G_{max} = -5.1 dBi and $\eta_{r_{max}}$ = 8%). Moreover, the optimal 3.6 GHz loop has higher gain and radiation efficiency, and it is considerably smaller than the optimal UHF counterpart ($G_{max} = $ -14.2 dBi, $\eta_r = 0.3\%$, and $L_{opt} = 45$ mm [3]). This results in a significant advantage for miniaturization and for packing several antennas within the area of a medical-grade plasters.

The achievable read range can be estimated through (2) using the chip sensitivity of a passive UHF-RFID chip, $p_t = -15$ dBm [4], an Effective Isotropic Radiated Power ($EIRP = P_{in}G_R$) of 4 W, and a gain of the loop G_{max} of -5.1 dBi. The 3.6 GHz loop achieves a read range of 1.3 meters that is comparable with that at UHF.

The higher gain provided by the loop and the corresponding higher available bandwidths at 5G will enable relevant data-rates for the 5G-RFIDs. By assuming a BPSK modulation, the tag data rate ($R = 2B$, with B being the RF bandwidth), and the Signal-to-Noise Ratio (SNR) are related by the equation:

$$SNR|_{dB} = P_{R\leftarrow T}|_{dB} - BT_0 k_B|_{dB} - NF, \qquad (3)$$

with $P_{R\leftarrow T} = p_t G_T G_R M \left(\frac{c}{4\pi f r}\right)^2$ being the backscattered power reaching the reader, $T_0 = 290$ K being the system temperature, and $k_B = 1.3810^{-23}\ \frac{m^2 kg}{s^2 K}$ the Boltzmann constant. By imposing a minimum SNR = 10 dB, an EIRP = 4 W, a reader antenna gain $G_R = 6$ dBi, a modulation index M = -6 dB, and a receiver noise figure NF = 10 dB, the maximum tag data-rate R can be extrapolated from (3) for the single epidermal loop at 3.6 GHz placed one meter away from the reader and with gain G_T = -5.1 dBi. It corresponds to a theoretical value of 0.52 Gbps that is, however, an upper-bound since the real achievable speed will be related to the specific frequency and bandwidth allocation of the 5G spectrum.

The safe implementation and the social acceptance of an epidermal microwave sensor requires an investigation about the human exposure to the radiated electromagnetic fields. Using Sim4Life 5.0, fields induced into the human body at 3.6 GHz by a nearby source have been evaluated through the Specific Absorption Rate (SAR) for conservative arrangements (reader-to-face distances of 20 cm and 5 cm). Results are reported in Fig. 3 and are below the FCC limits.

IV. Conclusion

Overall, the presented results demonstrated that, if a future generation of 5G-RFID tags and readers will guarantee at least the same sensitivities as in UHF and if the same power levels could be emitted, then an epidermal 3.6 GHz loop can offer read ranges comparable to those at the UHF bands. The 3.6 GHz loop looks particularly attractive, even against conventional UHF, in terms of both size (17.5 x 17.5 mm^2) and achievable data-rates (0.52 Gbps). More experiments to exploit above results will be the topic of future research.

Acknowledgment

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