Upper-bound Performances of RFID Epidermal Sensor Networks at 5G Frequencies

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***Abstract*—5G will play a key role in developing high speed wearable and epidermal electronics for healthcare applications such as patient monitoring, tele-surgery, and augmented sensorial abilities (both for humans and robots). At the same time, developing a 5G-RFID system based on backscattering communication will help reducing the power consumption and lowering the electronic complexity. Nevertheless, the high path losses and the strong electromagnetic interactions of the skin might severely limit ranges and performances of epidermal RFIDs operating at 5G frequencies.**

In this paper, the effects of the human skin on the link budget of epidermal RFID dipoles at microwave and mmWave frequencies are investigated through numerical simulations. Results show that an epidermal RFID sensor tags can reach ranges comparable with UHF systems by using either a single dipole at 5.8 GHz or a 23-element array of dipoles at 60 GHz when using the currently available chip sensitivities (-15 dBm) and reader antenna gains (6 dBi). Smaller antenna sizes of a 5G RFID sensor will allow the integration of tags in new ubiquitous non-invasive epidermal and wearable electronics, while the high frequencies will enable tracking with mm- and micro-scale resolutions for medical applications (e.g.: micro-ablation or muscular and neural rehabilitation).

***Index Terms*—5G, RFID, backscattering, epidermal sensors, 5.8 GHz, mmWave.**

I. INTRODUCTION

FIFTH generation (5G) wireless communication systems pledge to provide a massive amount of bandwidth, low latency, and multigigabit-per-second (Gbps) data rates through both the sub-6 GHz bands (e.g.: 5.8 GHz) and the mmWave frequency spectrum[1].

5G technology, therefore, enables new wireless solutions that go beyond the cellular network improvement. In particular, 5G is expected to significantly advance the deployment of wireless health-care sensing and monitoring applications for high-speed wearable Personal Area Network (PAN) devices. Within wearable applications, Epidermal Electronics [1] move wireless sensors from clothes and personal accessories directly to the human skin for the continuous assessment of people's health and well-being. Arrays of epidermal sensors at microwave and mmWave frequencies, with sizes comparable or even smaller than conventional Ultra High Frequencies (UHF, 860 - 960 MHz) antennas, could stream data, for retransmission to base stations or for processing, to nearby hubs such as cell phones, smart watches, augmented reality glasses or gloves, and virtual reality headsets (Fig. 1).

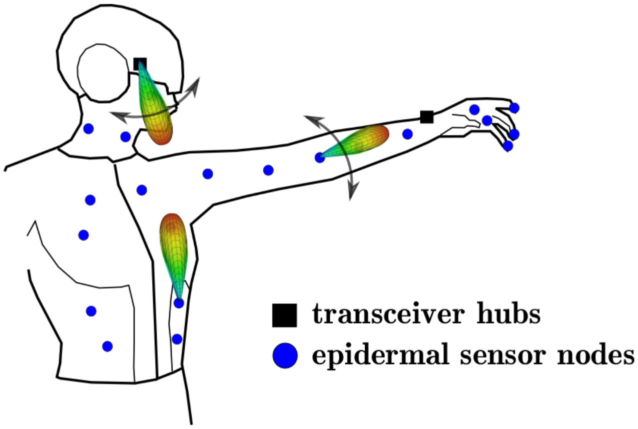

Fig. 1. Concept of epidermal sensor network at mmWave frequencies transmitting data to nearby hubs (smart watch and and virtual reality headsets).

Epidermal Antennas at 5G frequency bands are a new challenge since only modest knowledge is currently available about their interactions with the human body at these high frequencies. Some researchers explored the effects of mmWave radiations on the human body in terms of skin complex permittivity, heating and penetration depth [2]; one example of experimented 60 GHz wearable antenna for off-body communications was presented in [3]. Finally, researchers in [4] explored the advantages of having small arrays at microwave frequencies for on- and off-body sensors placed on clothes.

As epidermal antennas require a flexible substrate adhering to the skin, the reduction of the on-board electronic complexity is necessary to achieve low cost and comfortable devices. Moreover, the increasing number of ubiquitous wireless devices carries an energy burden and rises the problem of power source and battery disposal that needs to be addressed and solved. In this view, backscattering communication architecture enabled by passive Radio Frequency IDentification (RFID) technology can be an interesting solution also for future 5G epidermal links for the new generation of body sensor networks since they do not need local batteries to operate and require a minimized number of electronic components. However, the feasibility of a backscattering-based link among epidermal antennas in the 5G frequency bands is still in question due to both the high propagation and the high human body losses at these frequencies.

This paper investigates the achievable upper-bound performances of a 5G RFID epidermal sensor network by means of numerical analysis with the purpose of estimating the optimal antenna size and the maximum read distance that can be expected by a future generation of 5G RFID transponders.

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[1] Promising bands are 24.5-29.5 GHz; the license-free band at 60 GHz; and the E-band at 71-76 GHz, 81-86 GHz, and 92-95 GHz.

TABLE I
PARAMETERS OF THE COLE-COLE MODEL FOR WRIST/FOREARM AT MMWAVE FREQUENCIES, AS IN [6]

σ_s	ϵ_∞	$\Delta\epsilon$	τ (ps)	α
0.5	8.35	20.5	7.13	0.064

Performances are evaluated as function of the power sensitivity of the transponder electronics when either single- or multi-antenna elements are used.

II. RATIONALE

Epidermal Antennas communicate with an external receiver, but they need to physically interact with the body to collect, for example, biochemical skin parameters (temperature, sweat, pH). Since a thick substrate or a ground plane would prevent these type of interactions to happen, epidermal antennas are either directly attached onto the skin or, at most, placed on a sub-millimeter flexible membrane. Multilayered structures or patch antennas are, therefore, not suitable for these applications. This study on 5G-RFID epidermal antennas focuses on planar dipoles laid over the skin at three possible 5G operating frequencies of 5.8, 28 and 60 GHz.

The human skin consists of two primary layers: an outer epidermis (60 - 100 μm) and an underlying dermis (1.2 - 2.8 mm); the surface layer of the epidermis is called stratum corneum with a thickness of 12 - 18 μm [2]. Since radio waves penetration at sub-6 GHz bands exceeds the typical skin thickness, a three-layer model was used to account for the effect of both skin, fat, and muscle. Instead, at mmWave frequencies, a single-layer skin model is enough to reliably evaluate reflection and electromagnetic penetration in the skin since more than 90% of the transmitted electromagnetic power is absorbed within the epidermis and dermis layers and little power penetrates further into deeper tissues [2].

Skin permittivity values at mmWave frequencies are either extrapolated from experimental data collected at microwave frequencies [5], or were directly measured at frequencies ranging from 10 to 60 GHz to derive the Cole-Cole model [6]:

$$\epsilon^* = \epsilon_\infty + \frac{\Delta\epsilon}{1+(j\omega\tau)^{1-\alpha}} + \frac{\sigma_s}{j\omega\epsilon_0}, \tag{1}$$

whose parameter values, for the wrist/forearm case, are listed in Tab. I. Since these results are based on experimental data, they are considered more accurate to perform the simulations at mmWave frequencies (28 and 60 GHz) and, therefore, they were used in this work.

In a backscattering-based link, a transceiver (the reader) interrogates and remotely powers up a sensor (the tag). The round-trip monostatic free-space link budget of such configuration is defined as:

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

where $P_{R\leftarrow T}$ is the backscattered power from the tag received at the reader, P_{in} is the reader transmitting power reaching the transmitting antenna, G_R is the gains of the transmitting/receiving reader antennas, G_T is the gain of the tag, M is the modulation factor (M = 0.25 for passive tags, while $M > 1$ for tunneling tags [7]), τ is the power transmission coefficient at the tag/chip interface, η the polarization mismatch, r is the distance between the reader and the tag, c is the speed of light, and f is the carrier frequency. The tag activates when the power reaching its circuitry:

$$P_{R\rightarrow T} = P_{in} G_R G_T \tau \eta \left(\frac{c}{4\pi f r}\right)^2, \tag{3}$$

exceeds the tag sensitivity p_t. Since the aim of this work is to derive the upper-bound performances of the 5G RFID link, it is assumed $\eta = 1$, i.e. co-polarized transmitting and receiving antennas, as well as the power transmission coefficient at the tag/chip interface is set to $\tau = 1$. Tag antennas can be well matched to their reference impedance through T-match, Gamma-match, or loop-match [8]. RFID sensors are usually limited in the forward link where the maximum reader-to-tag distance is:

$$r = \sqrt{\frac{P_{in} G_T G_R}{p_t}} \frac{c}{4\pi f}. \tag{4}$$

System engineers can improve the forward link by tuning one or more parameters in Eq. 4, i.e. the antenna gain G_R of the reader and the antenna gain G_T of the tag.

Designing an RFID system to operate at microwave and mmWave frequencies might sound counter-intuitive since higher values of f increase the path-losses, thus producing a reduction in the maximum achievable r. Nonetheless, defining the antenna gains in terms of free-space effective apertures A_e,

$$G = \frac{4\pi f^2}{c^2} A_e, \tag{5}$$

the power collected by the circuitry of the transponder in Eq. 3 can be rewritten as:

$$P_{R\rightarrow T} = P_{in} A_{e_R} A_{e_T} \left(\frac{f}{cr}\right)^2. \tag{6}$$

Thus, if mmW antennas with the same effective aperture as in the UHF band are assumed (i.e. same spatial footprint and high aperture efficiency) the overall power $P_{R\rightarrow T}$ collected by the sensor can, in theory, be even higher than that at UHF bands. This is possible by replacing the single antenna for both the reader and the epidermal sensor with an array that is compressed in the same few centimeters footprint of a conventional UHF epidermal antenna. The gains of the resulting devices are hence expected to significantly improve, as shown later on.

III. SIMULATIONS AND RESULTS

For the sake of simplicity, the upper-bound performances of 5G epidermal antennas are explored by considering straight dipoles, but it is expected that similar results could be achieved for meander lines and loops which are also typical epidermal antennas at UHF. It was hence investigated how the length of epidermal dipoles affects their gains and their radiation efficiencies when placed at distance d = 0.25 mm from the body as in the case of a hosting membrane or plaster. Fig. 2 shows that, for a 5.8 GHz dipole, there exists an optimal

TABLE II
SKIN PERMITTIVITY AND CONDUCTIVITY VALUES AT 5.8, 28, AND 60 GHZ ON WRIST/FOREARM

Layers		f (GHz)		
		5.8 [5]	28 [6]	60 [6]
Skin	ϵ_r	35.1114	16.6491	11.6134
	σ (S/m)	3.717	14.6466	22.3201
Fat	ϵ_r	4.9545	-	-
	σ (S/m)	0.29313		
Muscle	ϵ_r	48.485		
	σ (S/m)	4.9615		

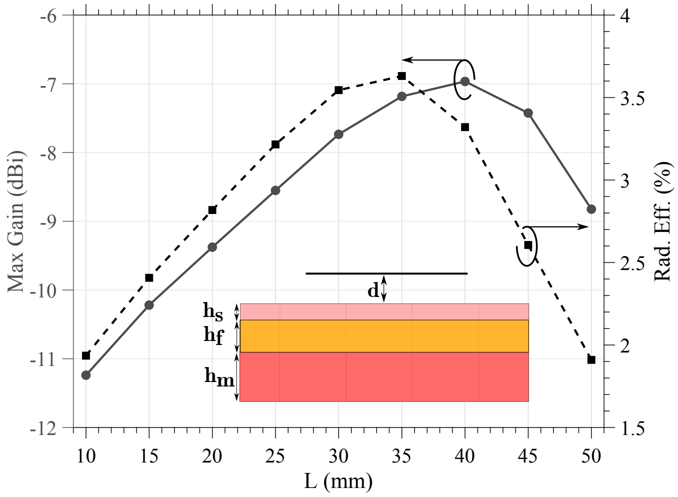
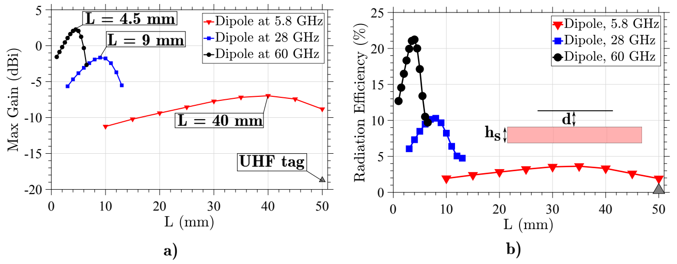


Fig. 2. Max gains and radiation efficiencies of an epidermal dipole at 5.8 GHz as a function of its length L. Inset: geometry for skin numerical modeling at 5.8 GHz, with h_s = 1 mm (skin); h_f = 3 mm (fat); h_m = 31 mm (muscle); d = 0.25 mm.

length ($L = 40$ mm) at which both the gain and the radiation efficiency are maximum (-7 dBi and 3.3% respectively); the optimal L is a trade-off between the radiation resistance of the antenna and the loss resistance due to the presence of the skin. A similar study was made at 28 and 60 GHz and reported in Fig. 3 where it is shown how a 60 GHz dipole with $L = 4.5$ mm achieves a much higher gain (2.3 dBi) and radiation efficiency (21.2%) than the 5.8 GHz and 28 GHz ($L = 9$ mm) counterparts. Overall, both microwave and mmWave epidermal dipoles have higher gains and higher radiation efficiencies when compared with the corresponding upper bounds of the epidermal UHF dipoles, whose maximum gain and radiation efficiency are -18.7 dBi and 0.3%, respectively [9]. This is a relevant result, especially considering the higher losses of the skin at higher frequencies. A possible explanation is that the skin is mostly acting as a reflector rather than an absorber as also predicted by the 1D propagation model in [2] and measured in [3].

Operating at microwave and mmWave frequencies allows to fit several antenna elements in a very small footprint (Fig. 4) and to obtain high values of gains that compensate the higher path-losses experienced at these frequencies. A 23-element array of dipoles at 60 GHz were simulated when placed at $d = 0.25$ mm away from the body, as before. The obtained gain (Fig. 5) is 23 dB higher than that of a single 5.8 GHz dipole and 35 dB more than a conventional epidermal dipole at UHF band, of course at the price of a reduced visibility angle (beam width).



a)

b)

Fig. 3. Epidermal dipoles at UHF, microwave, and mmWave frequencies. a) Max gains, and b) radiation efficiencies as function of the dipole length L. Inset: geometry for skin numerical modeling at mmWave frequencies, with h_s = 2 mm (skin), d = 0.25 mm.

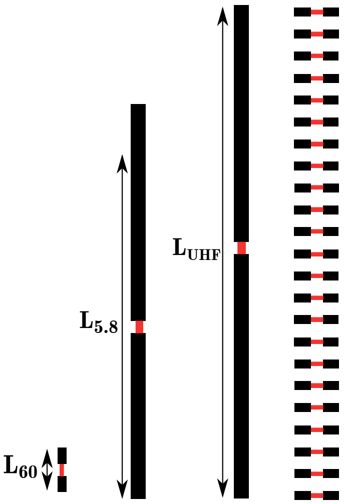


Fig. 4. Comparing sizes of epidermal antennas. At 60 GHz, an array of 23 dipoles spaced by $\frac{\lambda}{2}$ is as big as a UHF epidermal dipole; $L_{UHF} = 50$ mm [9], $L_{5.8} = 40$ mm, $L_{60} = 4.5$ mm.

IV. LINK BUDGET OF A 5G-RFID WEARABLE SYSTEM

With the obtained results, it is possible to discuss the feasibility of an RFID link at microwave and mmWave frequencies for epidermal sensor networks and to point out advantages and possible limitations. The maximum achievable reader-to-tag distance R_{max} of Eq. 4 was evaluated for different values of tag sensitivity p_t, while keeping fixed both the transmitted power (P_{in} = 30 dBm) and the antenna gain (G_R = 6 dBi) of the reader. In Fig. 6, four types of epidermal RFID sensor links are compared: the 60 GHz link with i) a dipole, and ii) a 23-element array, iii) the 5.8 GHz, and iv) the UHF (870 MHz) links both with only one dipole. For chip sensitivities of -15 dBm, both the 5.8 GHz dipole and the 23-element array at 60 GHz can achieve a maximum distance of 0.5 m that is enough for the epidermal sensors to communicate with a nearby smart watch, phone and augmented reality glasses. Moreover, 5G-RFID link ranges comparable with those of traditional UHF epidermal sensors can be achieved by using

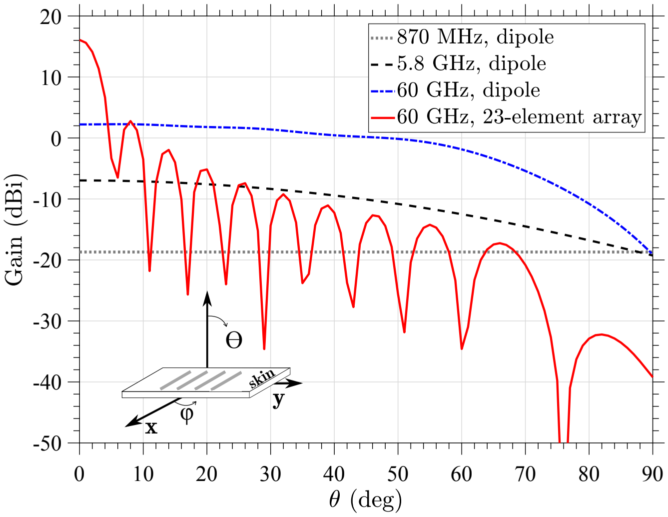


Fig. 5. Comparing gains of a epidermal dipoles at 5.8 and 60 GHz with a mmWave 60 GHz array of 23 elements, spaced by $\frac{\lambda}{2}$. Dipoles are placed at distance d = 0.25 mm from the skin; optimal dipole lengths were used: $L_{5.8}$ = 40 mm; L_{60} = 4.5 mm. The gain of a UHF epidermal dipole reported in [9] is used as reference. Inset: reference system and orientation of the dipoles.

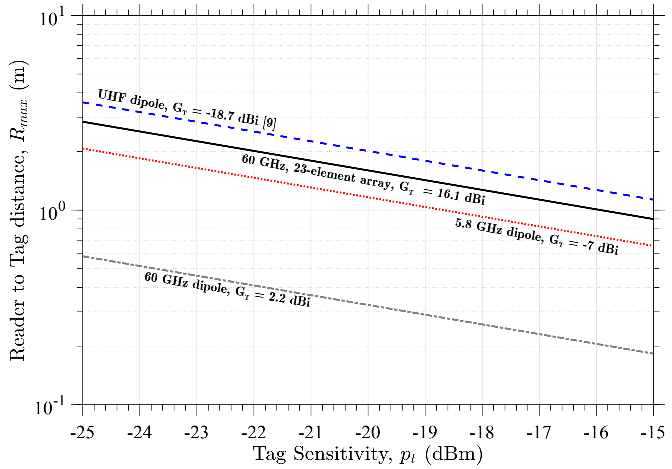


Fig. 6. Comparing forward-link ranges (Eq. 4) of several backscattering links as function of the tag sensitivity p_t when fixing the EIRP to 4 W (36 dBm): P_{in} = 30 dBm and G_R = 6 dBi. The simulated tag antenna gains G_T reported in Fig. 5 were used. The black solid line shows the achievable maximum forward-link range if a 60 GHz 23-element tag is used.

a 23-element array, but with the additional possibility to scan the beam.

V. CONCLUSIONS

The presented numerical analysis demonstrated that epidermal dipoles operating at microwave and mmWave frequencies provide higher gains than those at UHF. Moreover, the smaller size of each antenna element leaves space to deploy arrays with enough gains to counteract the propagation losses experienced at these higher frequencies. It was also shown that, by using typical RFID chip sensitivities and available reader antenna gains, ranges comparable to those at UHF bands can be reached either by an RFID epidermal mm-scale dipole operating at microwave frequencies (5.8 GHz) or by a mm-scale array of dipoles at mmWave frequencies (60 GHz).

Developing 5G backscattering systems brings several advantages to the existing RFID technology. For example, i) smaller sizes allow to better integrate tags in a plethora of new ubiquitous and non-invasive epidermal and wearable electronics; ii) higher gains can be obtained with arrays whose size is much smaller than a single UHF dipole; iii) the high frequencies enable tracking with mm- and micro-scale resolutions for medical applications (e.g.: micro-ablation or muscular and neural rehabilitation). Moreover, 5G RFIDs will be easily integrated within the automotive industry where mmWave radars are already being widely deployed thus stimulating new types of driver-car interactions. Finally, the integration of RFID readers within future 5G mobile devices will reduce manufacturing costs and make them available to several new users.

Although the results shown in this work suggest an upper-bound communication range for 5G RFIDs, it is important to stress out that ranges can be further improved if the same solutions currently explored at 5.8 GHz (e.g.: Van Atta arrays [10] and Tunneling Tags [11]) are adopted at mmWave frequencies as well. Future research will investigate loop antennas and beamforming through epidermal arrays as well as the effect of shadowing on the communication link.

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