Γ-Match Epidermal Loop for future 3.6 GHz 5G Body-centric Systems

Francesco R. Venturi ⁽¹⁾, Cecilia Occhiuzzi* ⁽¹⁾, and Gaetano Marrocco⁽¹⁾ (1) DICII- University of Roma "Tor Vergata" http://pervasive.ing.uniroma2.it * cecilia.occhiuzzi@uniroma2.it

Abstract

Wireless Epidermal Electronics gives the opportunity to directly and automatically sample health parameters at the skin level. Promising performances and pervasive applications could be achieved by exploiting the upcoming 5G communication systems. In this context, this work designs and experimentally investigates the performance of an epidermal *one-lambda* loop. A 12.5x12.5 mm layout provides a gain of -6.5 dB when directly stacked on the human phantom and, thanks to the Γ -Match, a bandwidth of approximately 20% is achieved.

1 Introduction

Epidermal Wireless sensors operating at microwave and mmWave frequencies could open up new paradigms for monitoring health parameters of multiple users in real-time and without using cables [1]. Compared to more assessed wearable devices, epidermal sensors are capable to collect biophysical data directly on the skin, for instance by sampling sweat such to retrieve pH, lactate, electrolytes and cortisol or by performing temperature, ECG and EMG measurements. The highest simplification to the electronics and hence the best compliance with the human body can be achieved by backscattering-based communications, like Radio Frequency Identification (RFID) [2]. In recent years, several epidermal sensor tags have been proposed for the UHF (860-960 MHz) band. Early studies [3] demonstrated that interesting opportunities could arise also from the exploitation backscattering-based of communications within the upcoming 5G communication systems, especially in the sub-6GHz band. Namely, in spite of the higher free space attenuation, 3.6 GHz on-skin antennas are suitable to provide comparable read distance to state-of-the-art UHF epidermal sensor tags, while boasting smaller layout and much higher data rate.

One-lambda loops are largely recognized as suitable for epidermal antennas [4]. Studies in the UHF and 5G S-bands demonstrated that optimal loop configurations exist [5], [3]. Namely, simulations suggested that at 3.6 GHz, a maximum radiation gain $G_{max} \approx -5$ dB could be achieved with a single 17.5×17.5 mm² loop placed 0.25 mm from the body. However, no attempts have be done to finalize

the design of the loop and to confirm the theoretical performances in real scenario. To the knowledge of the Authors, up to know, no epidermal antennas working at 3.6 GHz have been proposed.

In this paper, starting from the preliminary results in [3], a 3.6 GHz loop with embedded Γ -Match impedance transformer is presented. The performances are evaluated for direct on skin application and a preliminary experimental corroboration is obtained by measurements on a body phantom.

2 Layout

The layout of the *epidermal antenna* (Figure 1) comprises a squared loop of side L and an internal Γ -match transformer hosting the feeding point. The Γ -match works as impedance transformer, guarantees a fine control of the input impedance and contemporarily enables the direct connection to the unbalanced coax cable [6].



Figure 1 Layout of the Epidermal Loop including the internal gamma-match transformer and its equivalent circuit.

The equivalent circuital schematics is visible in Figure 1 too, with Z_g impedance of the transmission line given by the loop and the gamma road, Z_{loop} the center-side impedance of the loop in the absence of the gamma match connection and Z_{in} input impedance of the whole antenna towards the VNA. A capacitor *C* in series to the gamma rod is included to compensate the inductive reactance given by short-circuited transmission line formed by the loop element and the gamma rod. A micro SMD coax connector is located on the bottom face. For the sake of robustness and the easiness of fabrication and measurements, a 0.6mm FR4 ($\varepsilon_r = 4.3$, tg δ =0.025) PCB is considered as substrate and placed in direct contact with the human skin.

The antenna is designed through FDTD simulations (performed with CST Microwave Studio), including an 80x80 mm² 3-layers body phantom [3] as visible in Figure 2.



Figure 2 Multilayered phantom simulating the human body. Relative permittivity, electrical conductivity, thickness (Skin 1 mm, ε_r =36.92, σ =2.08 S/m - Fat 3 mm, ε_r =5.16, σ =0.16 S/m - Muscle 31 mm, ε_r = 51.32, σ = 2.65 S/m).

The design of the antenna was accomplished by a two-step procedure. Firstly, the optimal size of the loop was identified by acting on the length *L* of the side. Only the external loop is considered. Results are shown in Figure 3. An optimum value L_{opt} exists for L=13.5 mm. However, since a broadside direction is required, a sub-optimum value of L=12.5 mm was finally chosen, corresponding to $G_{max}=-6.4$ dBi and a radiation efficiency $\eta=-11.9dB$. In agreement with typical epidermal loops [7], when $L=L_{opt}$, a symmetric distribution of currents is visible (inset of Figure 2.a). Two facing sides host in-phase currents that produce radiation and power loss in the body. The other two sides host currents with opposite phase and contribute only to the

power loss. Nulls are located in the middle of the non-radiating sides leading to a linear horizontal polarization.



Figure 3 Radiation performances vs Side Length L. a) Maximum Gain and radiation efficiency, b) Main Lobe Direction

Once the optimal size was retrieved, input impedance was optimized by acting on the Γ -match rod L_1 and on the value C of the SMD capacitor in series with the rod. The former mainly impacts on the real part of the input impedance, the latter instead determines the resonance frequency f. Space between loop and rod d was kept small such to slightly impact on the current distribution. Results are visible in Figure 3.

By considering C=0.27pF and $L_1=6.5$ mm (other parameters in the caption of Figure 3), the input impedance is $Z_{in}=50.1$ - $j0.2 \Omega$ @ 3.6GHz, corresponding to $S11\approx-60dB$ and $BW_{-15}\approx20\%$. Thanks to the Γ -match, the layout has a large bandwidth, hence with benefits in compensating typical detuning effects due to human variability [2].

The achieved maximum gain in the broadside direction $(G_{max}=-6.6 \ dBi)$ is fully comparable with that of the bare loop layout in Figure 2. The small reduction (less than 0.5dB) is due to the additional power loss in the body generated by the high currents onto matching network. It is worth highlighting that the Γ -match efficiently acts as a balun being negligible the impact on the current



distribution and on the radiation pattern, as visible in Figure 4.

Figure 3 Input impedance (a) and S11 (b) of the optimal loop with {L=12.5, w=1, w1=0.4, d=0.5, L1=6.5, L2=10, C=0,27pF}mm

3 Prototype and test

A prototype of the loop (Figure 5 a.) was manufactured through the 4MILL300 ATC milling machine. A microcoax cable for connecting to VNA and a Murata GJM1555CHR27BB01 capacitor were integrated to the board. To guarantee a robust interconnection, the micro SMD coax connector was soldered on the top face of the PCB instead than on the bottom side as in simulation.

A cubic phantom (roasted pork with estimated parameters $\epsilon r = 40$, $\sigma = 2$ S/m [3]) was used for measurements. To reduce the impact of the cable, two precautions were taken. Firstly, the coax cable was disposed orthogonally to the currents that flow on the loop and secondly, it crossed the whole phantom and connected the VNA on the back (Figure 5 b). The latter configuration assures a double shielding effect: one given by the phantom itself and one given by the strong attenuation of the currents flowing on the external conductor of the coax produced by the

proximity (contact) of the lossy tissues. In this condition, the radiation for the disturbing currents is prevented.



Figure 4 Radiation pattern of the loop integrating the Γ -match and of the bare loop.

S11 was measured through Anritusu MS2024A Vector Network Analyzer. Results are in Figure 6. Due to uncertainties related to phantom, capacitor, manufacturing and mainly to the position of the coax connector, a post-fabrication retuning was necessary. By using a capacitor of C=0.4 pF in place of the expected 0.27 pF one, resonance frequency was perfectly tuned to 3.6GHz (S11~ -45dB). The prototype confirms the extremely good performances in term of bandwidth.

A preliminary evaluation of the radiation performance of the loop was done by applying the gain-comparison method [6]. A reference patch antenna with known gain [8] was measured on the same body phantom and in the same geometrical arrangement of the loop under test. By neglecting in first approximation impedance and polarization mismatching effects and cable losses, a Gmax~-6.5 dB was retrieved, that is fully in line with the simulations.



Figure 5 Prototype of the loop and connection to the VNA

5 Conclusion

A loop antenna operating at 3.6 GHz and suitable to be directly attached onto the human skin for body-centric communication was optimized, manufactured and tested. In agreement with previous studies, an optimal configuration exhibits a broadside $Gmax \sim -6.5 dB$. The Γ -match permitted to achieve a bandwidth of more than 20%. Following the model in [3], the estimated data rate could reach up to 0.52 Gbps for backscattering-based communication with an external reader.

Design and prototyping activities are currently ongoing to overcome the limitations of the presented layout and realize a fully epidermal antenna. Biocompatible silicon rubber-based polymers such as *Silbione* and *Ecoflex* are under investigation for acting as flexible substrate and for encapsulating the device. Strategies to perform measurements directly on the human skin are in developing too. Results will be shared during the Symposium.



Figure 6 Measured and simulated S11.

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