An UWB Coplanar Waveguide Fed Integrated IFA Design for Wearable Communications

Jinxin Du[1] and Christophe Roblin[1]
[1]COMELEC department, Télécom ParisTech (Institut Mines-Télécom and LTCI), Paris, France,
jinxin.du @ telecom-paristech.fr

***Abstract*—An UWB CPW-fed Integrated "IFA-like" design is proposed. The new design has a much longer short-ended arm and a much narrower gap between the radiating arms and the coplanar ground plane. The bandwidth increase is achieved thanks to the superposition of multi-resonances induced by the joint effects of a strong coupling between the radiating arms and the ground plane and the excitation of both even and odd CPW modes in the feedline. The design has been tested for two types of substrate, FR4 and denim, for which –10 dB bandwidths of more than 60 % and 87 % are achieved respectively. Body proximity effects are analysed for the denim IIFA by simulation. It shows that the antenna remains working well in the presence of human body thanks to its UWB feature. This extremely simple, low-profile and easily integrable UWB IIFA-like design can be used for wearable communications (on-body/off-body), supporting multi-standards.**

***Index Terms*— Coplanar, integrated IFA, UWB, wearable communications.**

I. Introduction

Since recent years, wearable antennas are gaining exceptional research attention due to their vital roles in wearable communications such as the Wireless Body Area Network, WBAN (or Wireless Body Sensor Network, WBSN). Appropriate wearable antennas should verify good properties such as low-profile, light weight, easy integration, etc. and particularly, should be robust to body proximity effects such as detuning, impedance mismatch, losses, etc. which are well known since long ago.

For minimizing the body influence, a simple and intuitive idea is to isolate the antennas from the human body by introducing a shielding layer. Large-size backing ground planes are the most commonly used for this purpose, for example, in patch antennas [1]. These antennas usually achieve excellent isolation, however, they have disadvantages such as either narrow bandwidth (≈ 6 %), or moderate [2] to large size, reduced flexibility and are mostly suitable for off-body (rather than on-body) radio links. Other solutions include metamaterial based, Artificial Magnetic Conductor (AMC) based or ferrite based screening layers [3]-[6]. They usually allow to have a good isolation while keeping a satisfactory to a relatively large bandwidth, but their thickness is generally significant and the overall size is large, which is quite inconvenient for integration into clothes. An alternative approach to improve the *resilience* of antennas to body proximity effects (notably the detuning effect) is to increase their bandwidth (BW) significantly – instead of resorting to isolation techniques (which often increase their complexity – design, size, cost, etc.). Of course, this approach does not prevent antenna/body Near-Field (NF) coupling effects, inducing extra losses and noticeable modifications of both NF and Far-Field (FF) patterns. In this context, one of the design objectives – considering as early as possible the body proximity effects – is notably to "monitor" losses (trying to maximize the total efficiency as much as possible), in order to achieve an interesting compromise between performance and complexity suitable for some applications. Thereby, planar ultra-wideband (UWB) antennas are interesting candidates for wearable communications. The above-mentioned body proximity effects still exist for UWB antennas, but their bandwidth is so wide that the possible detuning effects appear somehow more "globally" regarding the matching over the BW of interest (although for multi-resonant antennas each resonance can be affected). Therefore, possible abrupt radio link outage due to the collapse of the total efficiency which often occurs for narrow band antennas in the vicinity of a human body (when the detuning is such that the mismatch becomes extremely severe) is generally avoided for UWB antennas [7].

Among various antenna types, Coplanar Waveguide fed integrated Inverted-F Antennas (CPW-fed IIFAs) present interesting features such as large bandwidth as well as easy integrability; therefore, it is a quite suitable candidate for wearable communications. In [8], a folded CPW-fed IIFA printed on FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.025$, h = 1.6 mm) is proposed. The radiating element of the antenna measures 25 × 8 mm^2, for an overall size including the ground plane as large as 50 × 60 mm^2. This antenna achieves a –10 dB bandwidth of about 20 % around 2.045 GHz. In [9], a general design of a wideband CPW-fed IIFA, based on a design proposed in [7], is presented. The shorted end and open end horizontal strips being close enough to the CPW ground plane "patches", their coupling is strong and they can be viewed as asymmetrical coplanar strip (ACPS) [10]. In addition, the IFA is asymmetrically fed by the CPW which induces an additional resonance of the ground plane (explicable by the theory of characteristic modes). This resonance is close enough to the classical IFA resonance so that the bandwidth is increased to more than 40 % for a FR4 based IIFA and to about 25 % for a denim ($\varepsilon_r = 1.7$, $\tan\delta = 0.05$, h = 0.76 mm) based IIFA.

In this paper, we propose a new UWB small size CPW-fed "IIFA-like" design, as shown in Fig. 1. The design has quite similar form as classical IIFAs except that the short-ended arm is much longer and the gap between the radiating element and the coplanar ground plane is much narrower than conventionally. This special choice of the geometry leads to different mechanisms of radiation compared to classical IIFAs (hence the terminology "IIFA-like"). Indeed, it allows to create strong coupling between the radiating arms and the coplanar ground plane, and also to excite both the even mode (i.e. the CPW fundamental mode) and the odd mode (i.e. the asymmetrical slot-line mode) within the feedline. The combination of these factors results in close multi-resonances leading to a very significant increase of the bandwidth. We applied the new design with both FR4 and denim substrates. Full-wave simulations are performed for both antennas, and measurements are also carried out for the FR4 based IIFA. Results are presented and analysed below. It shows that the proposed design allows to achieve ultra-wide band for both antennas. Even in the presence of human body, the denim based IIFA can maintain quite good performance: the reflection coefficient $|S_{11}|$ is below –6.5 dB over a bandwidth of about 3 GHz, which remains a completely acceptable matching level, avoiding any dramatic radio link outage, as pointed out in the above paragraph. This compact UWB CPW-fed IIFA design can be suitable for wearable applications.

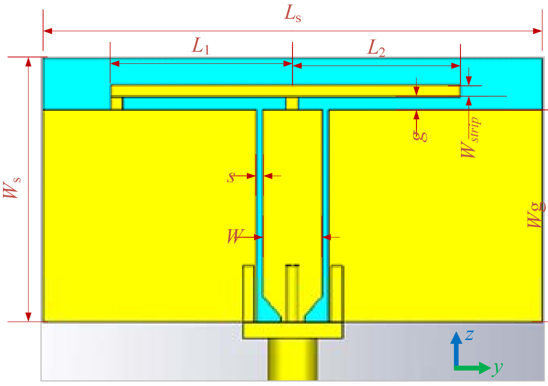


Fig. 1. Geometry of the proposed CPW-fed IIFA design.

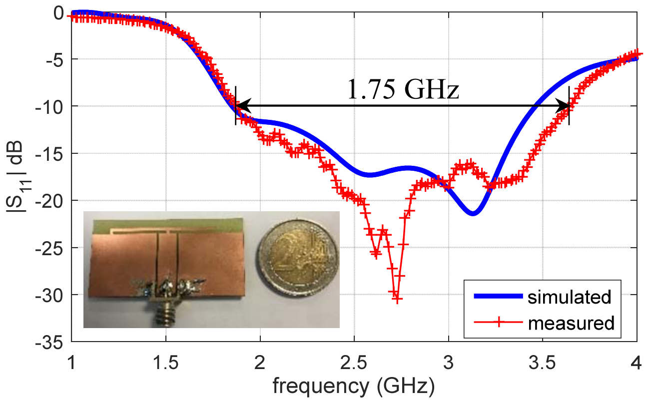
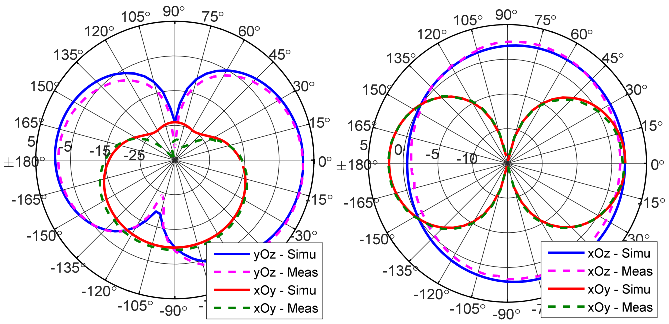
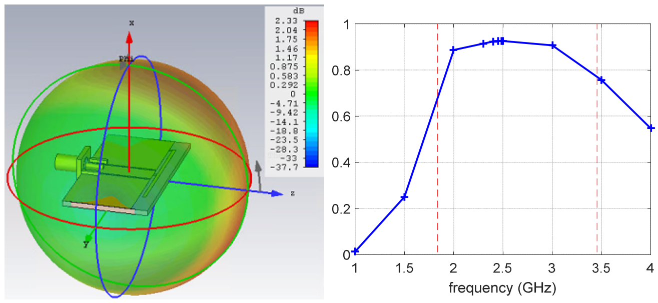


Fig. 2. Simulated and measured reflection coefficient $|S_{11}|$ of the proposed FR4 based CPW-fed IIFA.



(a) (b)

Fig. 3. Simulated and measured realized gain G_r in principle cut-planes of the proposed FR4 based CPW-fed IIFA: (a) $G_{r\theta}$ in yOz and xOy planes; (b) $G_{r\varphi}$ in xOz and xOy planes.



(a) (b)

Fig. 4. (a) 3D radiation pattern at 2.45 GHz; (b) total efficiency, of the proposed FR4 based CPW-fed IIFA in free space.

II. CPW-FED IIFA ON FR4 SUBSTRATE

A. Design of the antenna

In the first stage, the proposed antenna (Fig. 1) was designed with a commonly used FR4 substrate (relative permittivity $\varepsilon_r = 4.4$, loss tangent $\tan\delta = 0.025$ and thickness h = 1.6 mm). Dimensions are chosen for operation in the ISM band at 2.45 GHz. The radiating element is a horizontal strip which is fed at the middle by a 50 Ω CPW feedline (linewidth W = 6 mm, slot width s = 0.6 mm, length W_g = 21 mm), short-ended to the left (arm length L_1 = 19 mm) and open-ended to the right (arm length L_2 = 16 mm). The width of the strip is W_{strip} = 1 mm and the gap between the horizontal strip and the CPW ground plane is very narrow: g = 1 mm. The CPW feedline is chamfered at the edge to facilitate the connection to a 50 Ω SMA connector by welding. The overall size of the antenna is $L_s \times W_s$ = 50 mm × 26 mm.

B. Simulation and measurement results

The proposed antenna structure was firstly studied using the full-wave simulator CST® MWS. Note that the adaptive meshing functionality has been used for all simulations, so that they can be considered reliable and accurate. Then, a prototype was fabricated and measurements were carried out in a well-conditioned anechoic chamber. Fig. 2 shows the reflection coefficient $|S_{11}|$ from simulation (blue solid line) and measurement (red dash line). We can see that the –10 dB impedance bandwidth is 61.3 % (1.835 GHz – 3.455 GHz) in simulation and 63.3 % (1.89 – 3.64 GHz) for the measurement

– more than 10 % larger than that obtained in [9]. In Fig. 3 the simulated and measured realized gain patterns (G_r) in principal cut-planes for both θ and φ polarizations are compared. It can be seen that measurements and simulations are in relatively good agreement. Fig. 4 (a) shows the simulated 3D radiation pattern of the antenna at 2.45 GHz. A maximal G_r of 2.3 dBi is observed. We also point out that the antenna radiates significantly towards both the perpendicular broadside (+x) and the "end-fire" (+z) – i.e. in the antenna plane – directions, implying that both off-body and on-body communications can be supported. Fig. 4 (b) shows that the simulated total efficiency η_t ($\eta_t = \eta_e$ (1–$|S_{11}|^2$) with η_e the radiation efficiency) is between 70 % and 93 % over the whole –10 dB band.

The ultra-wide band is the result of superposition of multi-resonances close to each other. In fact, it can be seen from Fig. 5 that three resonances or anti-resonances (at which *Imag*(Z_{in}) = 0) are located within the –10 dB input BW (at 2.1, 3.05 and 3.36 GHz) and two others are very close (at 1.78 and 3.99 GHz). Conventional IIFA structures present generally only one resonance; in [9] an additional close resonance is created thanks to the technique already described, notably by coupling the CPW feedline and the ground plane. A thorough inspection of the current and E-field distributions allows to interpret the obtained multiple resonances as a multi-mode behaviour. Fig. 6 (a) shows the surface current density at the resonance of 3.05 GHz. We can see that there exists a strong coupling between the radiating arms and the CPW ground plane due to the high length of the short-ended arm and the narrow inter-gap. Fig. 6 (b) shows the E-field distribution (for two different phase values) in the vertical cut-plane at the SMA pin point. It can be seen that both the even mode and the odd mode are excited "in parallel" within the feedline. The same phenomenon has also been observed for almost all other resonances, except the one at 2.1 GHz for which only the fundamental even mode is excited. The latter can be considered as the "fundamental IIFA mode". In other words, our proposed design seems to behave as a parallel combination of a classical CPW-fed IIFA and an asymmetrical coplanar slot-line-fed IIFA. However, as the antenna is fed symmetrically, contrary to the design proposed in [7] or [9], no characteristic mode of the ground plane is excited.

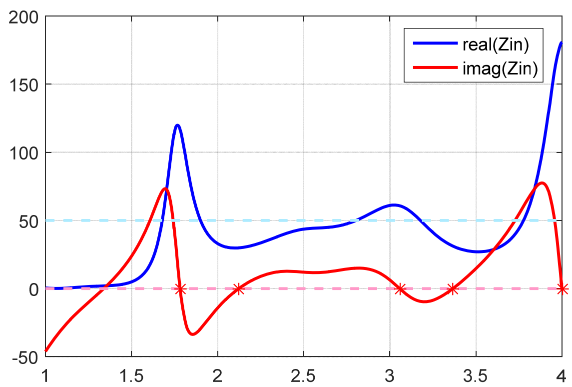


Fig. 5. Impedance (Z_{in}) of the FR4 based CPW-fed IIFA.

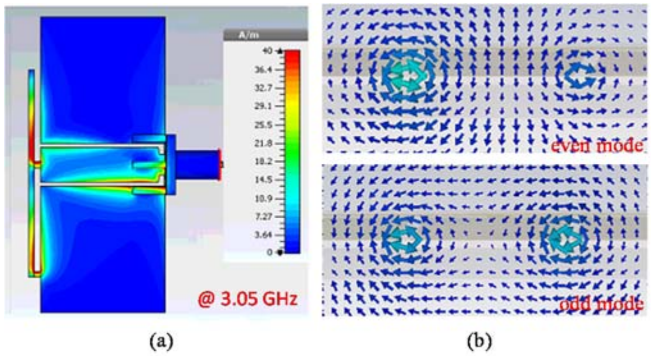


Fig. 6. (a) Surface current density distribution; (b) E-field distribution, in the vertical cut-plane at the SMA pin point for the FR4 based CPW-fed IIFA (at 3.05 GHz).

III. CPW-FED IIFA ON DENIM SUBSTRATE

A. Design of the antenna

In the second stage, we applied the same principle for designing an UWB CPW-fed IIFA on denim ($\varepsilon_r = 1.7$, $\tan\delta = 0.05$, h = 0.85 mm). The dimensions taken are comparable to previous values: L_s = 50 mm, W_s = 25.5 mm, W_g = 20.5 mm, L_1 = 19.4 mm, L_2 = 15.6 mm, W_{strip} = 1.2 mm, g = 1.3 mm, W = 6 mm, s = 0.6 mm. In particular, we took exactly the same dimensions for the CPW feedline after analysing the trade-off between the impedance matching and the antenna size. Actually, the design of a 50 Ω CPW feedline on denim would require a very high ratio of *W/s*, corresponding to either an excessively large strip or very narrow slots. However, none of them would be favourable for the practical fabrication and integration. Keeping the same dimensions increases the characteristic impedance to about Z_{cpw} ~ 67 Ω for the Denim version. Nevertheless, we'll see next that this value of Z_{cpw} operates an impedance transformation favourable to the overall performance of the proposed antenna.

B. Simulation results

In Fig. 7 the blue solid line shows the simulated reflection coefficient $|S_{11}|$ of the denim based IIFA in free space. It can be seen that the –10 dB input bandwidth is 2.99 GHz (1.92 GHz – 4.91 GHz), i.e. a relative BW of 87.6 %, which is very high for such kind of antenna, as far as we know. Fig. 8 (a) shows the simulated 3D radiation pattern at 2.45 GHz. A maximal G_r of 2.24 dBi is obtained. The radiation pattern is comparable to the previous one so that the same comments still hold with regards to on and off body usage. Fig. 8 (b) shows that the simulated total efficiency is between 70 % and 93 % over the whole operating band.

Fig. 9 illustrates the multi-resonances phenomenon: four resonances are located in the passband (at 2.15, 2.29, 2.855 and 4.39 GHz) and two other ones in the vicinity (at 1.75 and 5.05 GHz), consequently resulting in a widely enhanced bandwidth. Similarly to the FR4 substrate case, analyses on the current and E-field distributions reveal the reason for the induced multi-resonances: a combined effect of, 1) a strong coupling between the radiating arms and the ground plane, and

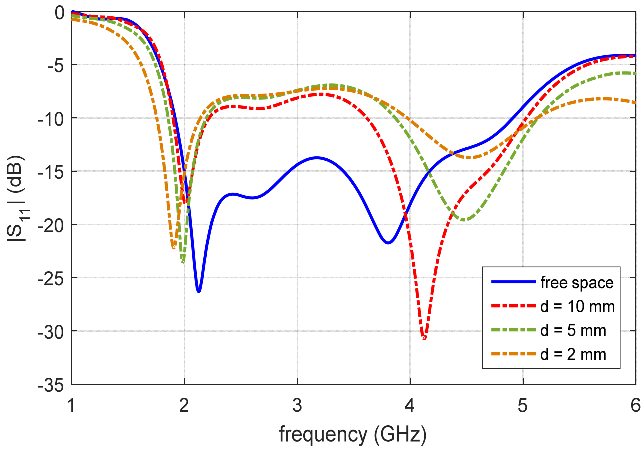
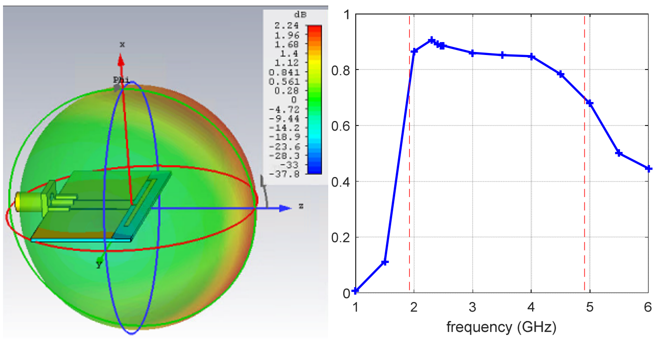


Fig. 7. Simulated reflection coefficient $|S_{11}|$ of the proposed denim based CPW-fed IIFA in free space and on the phantom arm at different distances.



(a) (b)

Fig. 8. (a) 3D raidation pattern at 2.45 GHz; (b) total efficiency, of the proposed denim based CPW-fed IIFA in free space.

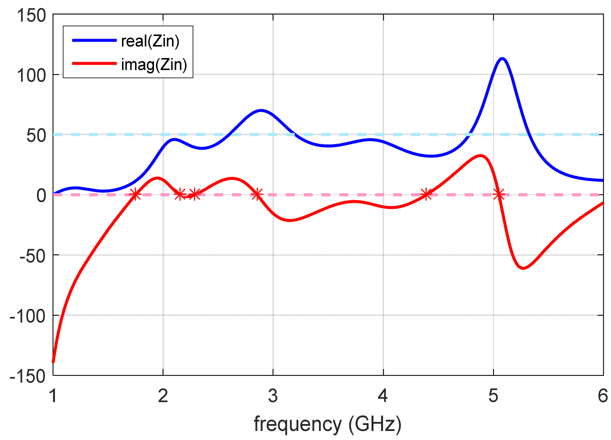


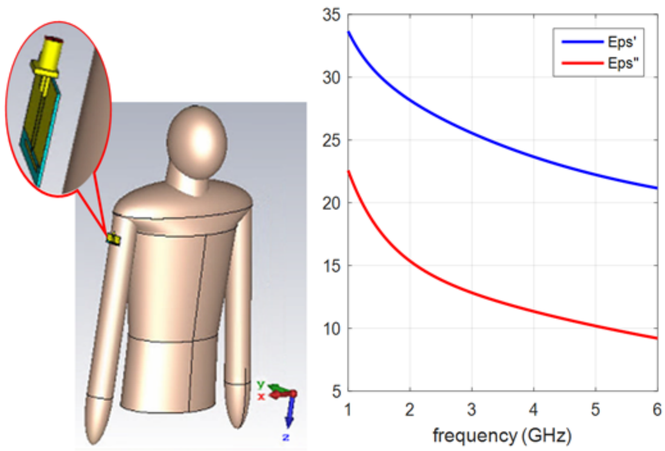
Fig. 9. Impedance (Z_{in}) of the denim based CPW-fed IIFA.

2) the excitation of both even mode (for all the 6 resonances) and odd mode (for the resonances at 2.15, 2.29 and 4.39 GHz) within the feedline.

C. Test on a body phantom

The proposed denim based IIFA can be easily integrated into clothes for WBAN communications. To verify its in-situ performance in the presence of human body, we carried out simulation tests with a canonical homogeneous phantom, as shown in Fig. 10 (a). The dispersion law (Fig. 10 (b)) of its effective medium is chosen to follow the measured values of a real body phantom used for experiments at our laboratory [11] (it is demonstrated in this article – amid others – that such simplified homogeneous phantom models designed with canonical geometries can be used satisfactorily in place of heterogeneous anthropomorphic phantoms for *external* electromagnetic problems). The antenna was placed on the phantom arm, near the shoulder, at a distance *d* of 10 mm, 5 mm and 2 mm. In Fig. 7, the dash lines illustrate the evolution of the reflection coefficient as the distance decreases, which calls for the following comments. First, the low cutoff frequency decreases because the phantom behaves as an "additional substrate layer" for the antenna. Given that the phantom has a much higher effective permittivity than denim, the antenna equivalent electrical size becomes larger. Second, the input impedance is affected by the antenna-body coupling, inducing a degradation of the reflection coefficient $|S_{11}|$ over a part of the band. However, the matching remains acceptable (the $|S_{11}|$ remaining below –6.5 dB for the worst case), avoiding any dramatic radio link outage as pointed out in the introduction. Third, the BW is enlarged because the phantom operates as a dissipative load lowering the antenna quality factor. Meanwhile, the total efficiency of the antenna is decreased to values over the input band between 30 % and 55 %, 18 % and 35 %, 9 % and 17 % respectively for the 10, 5, 2 mm cases. These preliminary tests with a body phantom justify globally the applicability of the proposed CPW-fed IIFA for wearable communications.

Note finally that this antenna can be used for multi-standard/multi-band applications as it covers, when used on the body, the GSM 1800, UMTS, WiFi (2.45 GHz and possibly "5 GHz"), LTE/LTE-A 2100 and 2600, and WiMAX (2.5 GHz, 3.5 GHz and possibly 5.8 GHz) bands.



(a) (b)

Fig. 10. Homogeneous phantom: (a) "IIFA – phantom" view; (b) dispersion law of the effective medium of the phantom.

IV. Conclusion

An extremely simple, compact, and small UWB CPW-fed IIFA design is proposed. A –10 dB bandwidth of more than 61 % and 87 % is achieved for FR4 and denim based realizations respectively. Tests with a phantom show that the body proximity effects are relatively moderate for the denim based IIFA. This antenna design can be suitable for wearable applications, including on-body and off-body communications and/or can support multi-standard applications. At the present time, the optimisation of the in-situ denim based IIFA (in order to improve the input matching and total efficiency) is still ongoing.

REFERENCES

[1] S. Sankaralingam and B. Gupta, "Development of textile antennas for body wearable applications and investigations on their performance under bent conditions", *Progress In Electromagnetics Research B*, vol. 22, pp. 53-71, 2010.

[2] Y.-F. Wei and C. Roblin, “Multislot Antenna with a Screening Backplane for UWB WBAN Applications,” *International Journal of Antennas and Propagation*, Hindawi Publishing Corporation, 2012.

[3] S. Zhu and R. Langley, ”Dual-Band Wearable Textile Antenna on an EBG Substrate,” *IEEE Transactions on antennas and propagation*, vol. 57, no. 4, pp. 926-934, 2009.

[4] C. T. Islam, M. Faruque, and N. Misran, “Reduction of specific absorption rate (SAR) in the human head with ferrite material and metamaterial”, *Prog. Electromagn. Res. C*, vol. 9, no. 4758, 2009.

[5] H. R. Raad, A. I. Abbosh, H. M. Al-Rizzo, and D. G. Rucker, "Flexible and compact AMC based antenna for telemedicine applications", *IEEE Transactions on antennas and propagation*, vol. 61, no. 2, pp. 524-531, 2013.

[6] R. Augustine, T. Alves, T. Sarrebourse, B. Poussot, K. T. Mathew, and J. M. Laheurte, "Polymeric ferrite sheets for SAR reduction of wearable antennas", *Electronics letters,* vol. 46, no. 3, pp. 197-198, 2010.

[7] C. Roblin *et al*, “Antenna design and channel modeling in the BAN context—part I: antennas,’ *Annals of Telecommunications*, Springer, vol. 66, n° 3-4, pp. 139–155, April 2011.

[8] Y. L. Kuo and K. L. Wong, "Coplanar waveguide-fed folded inverted-F antenna for UMTS application", *Microwave and optical technology letters*, vol. 32, no. 5, pp. 364-366, 2002.

[9] W. El Hajj, C. Person, and J. Wiart, "A novel investigation of a broadband integrated inverted-F antenna design; application for wearable antenna", *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 7, pp. 3843-3846, 2014.

[10] P. Hui, “Design of integrated inverted F antennas made of asymmetrical coplanar striplines,” *Appl. Microw. Wireless*, vol. 14, no. 1, pp. 28–37, Jan. 2002.

[11] C. Roblin, “A statistical assessment of ambient electromagnetic field using body-worn multiaxial sensors”, *Compte Rendus Physique (Académie des Sciences)*, Elsevier publisher., vol. 16, n° 9, pp. 802-818, Nov. 2015.