*Paper Title:*

# Wearable Antennas for Off-Body Radio Links at VHF and UHF bands (below 1 GHz): Challenges, State-of-the-Art and Future Trends

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## *Abstract:*

An in-depth survey of wearable antennas for off-body radio links in the VHF and UHF frequency bands (below 1 GHz) is presented. The review encompasses distinctive specifications, design criteria and challenges, material characterization procedures, antenna topologies and technologies, multi-antenna systems, dedicated testing procedures, applications and future trends.

## *Index Terms*

VHF antennas, UHF antennas, Wearable antennas, body-worn antennas, textile antennas, embroidered antennas, antennas for body-centric communications, antennas for body area networks, antennas for personal area networks, antennas for off-body wireless communications.

## 1. Introduction

There are several existing and forthcoming wireless applications that either require or can benefit from one or more antennas that are directly stitched on a piece of clothing or a garment, or integrated into a personal accessory (such as shoes, glasses, buttons, helmets). These antennas are usually referred to as body-worn antennas, textile antennas, BAN (Body Area Network) antennas, antennas for body-centric communications, wearable antennas. The last term is the one that is going to be used in this paper, as it denotes any antenna that is small and light enough to be worn or carried on one's body.

In the last decades, hundreds of scientific papers on wearable antennas have been published in the open literature [1-8]. Therefore, for the sake of completeness and clarity, a valuable analysis of the state-of-the-art on wearable antennas should be limited to antennas for a specific application, a given frequency range, or a chosen antenna technology. In this context, the present review focuses on wearable antennas operating in the VHF band and part of the UHF frequency band (below 1 GHz). Choosing 1 GHz as the upper boundary for this review is highly relevant, as the operating frequency is usually the main parameter to discriminate among available antenna topologies, technologies and characterization techniques. Moreover, we limit our discussion on antennas for off-body radio links, also excluding antennas integrated into mobile terminals/cases and operating close to the body. Specifically, only wearable antennas that can be used separately from the radio unit are of interest here.

VHF/UHF wearable antennas are mostly used in professional mobile radio communications for soldiers, emergency operators and law-enforcement personnel. VHF wearable antennas are applied for FM broadcasting reception [57,58] (87-108MHz), and reliable mobile communications for law-enforcement personnel [55,56] (at 30-80MHz), [59-62] (around 150MHz). At the UHF lower band, wearable antennas have been designed for personal and professional mobile radio systems operating around 400MHz [63-78] (as for example the TETRA [70] and TETRAPOL systems [73,74]) and digital television (DTV) broadcasting reception (470-770 MHz) [81-88]. Helmet antennas for narrowband tactical satellite communications at around 300MHz [79] as well as antennas to be integrated into soldier/police armor vests [69,70] have also been designed. Wearable antennas for the user terminal of satellite-based search-and-rescue systems (Cospas-Sarsat system at 406MHz) have been proposed in [89-93]. At the UHF upper band, wearable antennas operating around 868MHz [94,95,97-104], have been suggested for remote health monitoring systems, remote environmental parameters monitoring for rescue operators, security systems, portable short range radars for in-situ hazard monitoring, as well as in RF energy harvesting systems [105-107]. Both printed and textile wearable antennas operating at the UHF RFID 840-960MHz band can be used for remote wireless identification and tracking of persons [108-141].

As far as VHF/UHF wearable antennas are concerned, many of their distinctive features are related to the fact that the corresponding free-space wavelength ($\lambda$, with 30cm<$\lambda$<10m when 30MHz<f<1GHz) is larger than or at most comparable to the size of the human body sections the antenna can be attached to (torso, back, legs, arms, shoulders, head). These features impose some serious challenges to the wearable antenna designer, who is concerned with meeting two conflicting design requirements. On the one hand, he/she aims for maximum antenna performance in proximity of the human body. On the other hand, he/she must ensure that the wearable antenna can be invisibly and unobtrusively integrated into a garment, in order to ensure the wearer's comfort.

The present review paper has been organized as follows. Dedicated specifications, design criteria, materials and technologies for VHF/UHF wearable antennas are first summarized in Section 2. Then, the topologies of wearable antennas operating in the VHF band, UHF lower band and UHF upper band are reviewed in Section 3, Section 4 and Section 5, respectively. Special consideration has been given to antenna performance obtained by measurements on antenna prototypes, when the latter are worn on the human body or a body phantom. Section 6 is devoted to multi-antenna systems, which are designed with the aim of enlarging the antenna frequency bandwidth or spatial coverage, or to implement diversity schemes and beamforming architectures. Finally, concluding remarks and future trends are outlined in Section 7.

## 2. Design Criteria, Materials and Technologies for Wearable Antennas

The specific environment, in which wearable antennas operate, imposes explicit requirements and constraints that must be included in the antenna's design criteria. This then impacts the choice of materials and technologies to implement the antenna. We now first outline all relevant criteria that must be taken into account when designing wearable antennas for operation in the VHF/UHF bands. We then discuss the selection and electrical characterization of suitable fabrication materials and construction technologies.

### 2.A. Design considerations and criteria

Wearable antennas must be unobtrusive, in the sense that they do not limit the movements of the person wearing the wireless device. For some applications (soldiers, law-enforcement personnel), antennas also have to be rugged yet with a low visual signature. Furthermore, well-known mechanical requirements are lightweight, low profile, compactness, and flexibility (to make antenna conformable to the wearer's body). It directly follows that the tolerable extent for an unobtrusive wearable antenna is of the order of a few tens of cm, which is comparable to $\lambda$ at 1GHz, and significantly less than $\lambda$

at VHF-band frequencies. In Figure 1, the hypothetical physical size of an efficient radiator versus frequency is illustrated, to allow a direct comparison with the size of some body parts that can act as the antenna platform.

At frequencies lower than 1GHz, the antenna wearer cannot be considered electrically large, and for high-efficiency antennas (where performance is preferred over miniaturization that results in electrically small inherently inefficient antennas) the antenna size will be comparable to body size. Then, from an electromagnetic point of view, the body itself, being in the reactive near-field region of the antenna, becomes an important element of the antenna and affects the antenna performance. Main effects are reduction of the realized gain due to impedance detuning, cross-polarization level growth, radiation pattern fragmentation, and antenna efficiency decrease related to the power coupling into the lossy human body. Therefore, the body presence should be considered from the beginning of the design process. This approach differs from what is usually done when designing wearable antennas operating at microwave and millimetre wave frequencies, where the effects of the person wearing the antenna can be compensated *a posteriori*, by measurements and fine tuning of an antenna originally designed for free-space operation conditions. The body effect is substantial for VHF antennas [62], since the wearer’s body is entirely inside the antenna reactive near-field region. Also, some radiation absorption resonances are located exactly in the VHF band [55]: 70-80 MHz for whole-body SAR (Specific Absorption Rate), and around 300MHz for head SAR [10].

Due to the relatively large wavelength, clothing underneath or covering the antenna does not affect antenna performance (provided it is not wet, dirty, or electrically conductive) [88]. On the other hand, performance of wearable antennas integrated inside garments of firefighters and soldiers is also limited by a number of devices in proximity of the antenna (fire extinguisher, ammunition, hydration packs, etc.).

The human body behaves as an inhomogeneous lossy antenna platform with a high dielectric permittivity. As a reference, the relative permittivity and the effective conductivity are shown in Figure 2a for the muscle tissue [11], which is usually adopted as a human-tissue equivalent material in homogeneous phantoms and numerical models. The wavelength and penetration-depth into the muscle are also shown in Figure 2b. The high values of the relative permittivity of the human tissues (larger than 50) may only yield a small miniaturization effect with respect to the stand-alone antenna [57], as, in the lower frequency range, the body occupies a small percentage volume of the antenna’s reactive near-field region. Power absorption into the human body can help to improve the antenna return loss and meet wideband requirements, but the antenna radiation efficiency degrades. Indeed, measured efficiencies for VHF wearable antennas can be as low as a few percent. Efficiency decrease likely (but not necessarily) leads to antenna gain reduction compared with the free-space conditions.

Importantly, it is imperative that body-worn antennas satisfy SAR limits [10,12], to keep user RF-exposure below a harmful rate. Specifically, according to ICNIRP's guidelines in the 10MHz-10GHz frequency band, a whole-body average SAR of 0.08W/kg has been chosen as the restriction that provides adequate protection for public exposure. Moreover, the maximum 10g-averaged SAR in the head/trunk and limbs should not exceed 2W/Kg and 4W/Kg, respectively.

In the VHF band, there is no room to implement a large ground plane that decouples the antenna from the body, nor does the wearer's body act as an effective reflector to reduce back radiation and increase antenna gain. In a few cases, depending on the distance between the antenna and the body surface, an increase of the radiated field (with respect to the free-standing antenna) has been noted in the backward direction (instead of in the broadside direction), showing that the human body is operating as a director element at certain frequencies [57,96].

Conventional VHF antennas are bulky, and miniaturization techniques have been used to fit the antenna into clothing, life vests, and jackets (fractal geometries [59, meandering techniques [57,58, high permittivity ceramic materials, antenna loading with lumped components [62]). However, miniaturized antennas have low efficiency, and high permittivity dielectrics and magnetic materials increase antenna weight and cost. Wire antennas, strip antennas made of copper tape or embroidered wire antennas, all exhibit similar electrical performance in the VHF band. This is mainly due to the power absorption by the human body being the dominant loss mechanism [57], compared to the ohmic losses in the antenna conductive parts. To increase antenna efficiency, the size of the radiating elements has to be increased, hence requiring the development of flexible antennas that are made conformal to the body shape (dipole-like antennas [57,58], vest antennas [55,56]). As long wire VHF antennas are usually installed along body arms/legs, radiation pattern shape, null directions in radiation pattern, and field polarization are mostly affected by the posture of the antenna wearer and antenna position on the body [57,58].

At UHF band, antenna layouts can include a ground plane to shield the antenna from the human body. However, since it cannot be electrically large at the lower frequencies, it is not so effective to increase antenna gain. Moreover, by excluding a metallic reflector, the antenna can be thinner and more flexible. In addition, performance degradation can be observed in multi-layer grounded textile antennas, due to mechanical deformation and moisture absorption of the textile material used as dielectric layer to isolate the antenna conductive parts from the ground plane. Body effects become less pronounced as the operating frequency increases, because the electrical distance between the antenna and the body can be increased while still satisfying low-profile requirements, and a smaller body volume is affected by RF energy absorption as penetration depth decreases. The latter aspects also alleviates SAR issues.

For a selected on-body antenna location, postures and movements of the wearer harmfully affect both antenna radiation pattern and input impedance. The most critical case being when the antenna (or part of it) is mounted on the wearer's arms. Person-to-person variation in antenna performance is usually weaker than variation due the wearer posture and movements, and the distance between the antenna and the body surface. Wearable antennas are usually designed to be broadband to compensate for all above casual variations.

Several papers have been devoted to the analysis and design of VHF/UHF antennas integrated on helmets [60,61,79,80,104,145-148,155,156], as any soldier, policeman, firefighter, as well as motorcycle riders and bikers, wear such a head protection. The main advantages of a helmet antenna are related to its "prime location", represented by the body head. Indeed, due to the helmet natural shape, it is relatively easy to construct an antenna with a hemispherical pattern, or an azimuth-plane omnidirectional pattern with a deep null in the azimuth direction. Nonetheless, the surface available on a helmet for a low-profile and conformal antenna is rather limited, and sometimes such a surface has to be shared with other helmet-mounted devices, such as, for example, video cameras. Due to the limited and high-value of the room available on a helmet surface, wideband/multifunction helmet antennas are usually preferred with respect to narrowband helmet antennas.

### 2.B Materials and technologies

In order for an antenna to be wearable, one must combine a suitable selection of materials, both for the conductive and non-conductive parts, with an adapted antenna topology. This combination implements optimal performance in proximity of the human body by means of an antenna component that is invisibly and unobtrusively integrated inside a garment as well as comfortable and non-hindering for the wearer. Adopting textile fabrics as substrates [13,14] is then an obvious choice when one wants to integrate wearable antennas into garments. In 2000, Massey [38] was the first to propose fabric antennas that pair excellent radiation efficiency with maximum user comfort. As, for optimal performance, the antenna is a relatively large component, in particular in the VHF/UHF-frequency range, special care should be taken that the antenna together with the supporting structure is sufficiently flexible, albeit not drapable to protect then antenna against stress, compression [39] and crumpling [40], and to ensure stable antenna characteristics. In addition, permanent deformation of the antenna and supporting structure after temporary compression should be avoided by limiting the *compression set* [15] (CS<40% as a rule of thumb) of the adopted materials. Moreover, the module should be breathable, such that no excessive moisture is being trapped by the antenna. Exposing the antenna module to different relative humidity conditions may also result in water droplets that are absorbed by the textile antenna materials. This process will alter the antenna characteristics. In 2010, it was established that, to ensure stable antenna performance in different environmental conditions, hydrophobic fabrics should be preferred, with a low *moisture regain* [16] (MR<3, as a rule of thumb).

To implement the conductive parts, a number of wearable antenna fabrication technologies are available, some of which are shown in **Error! Reference source not found.**a-3d. The simplest approach is to integrate, knit or embroider conducting wires, copper tape or conductive yarns into a piece of clothing [41-43,45]. In 2004, Salonen et al. [33] assembled a dual-band antenna by mounting a U-slot patch, created in copper tape, on a fleece fabric substrate. In 2006, Kellomaki [57] integrated dipole arms made of 1-cm-wide copper foil tape inside a jacket to implement an FM-band antenna. Although conducting wires and copper tape are flexible, they are not breathable and they may affect the comfort of the person wearing the jacket. Therefore, they do not provide fully integrated textile antenna solutions. In 2005, Ouyang et al. [37] wove electrotextile microstrip antenna patches by combining conductive and non-conduductive yarns. These patches were simply taped onto a rigid Rogers HF board material. A more appropriate technique to realize full-fabric antennas consists of attaching e-textiles, which are typically copper or copper-nickel plated non-woven fabrics, to the textile substrate. In 2000, Massey [38] stitched the electrolessly copper-plated rip-stop nylon patch to the textile fabric substrate. Later, in 2008, it was found that a better connection and more flexibility can be obtained by making use of a thermally-activated thermal sheet [13,45] to assemble the different layers. Quite recently, embroidered patch antennas [46] gained in popularity, thanks to the availability of low-cost automatic embroidery machines that operate with conductive yarns, These machines enable the study of different embroidery patterns for antenna and ground plane, which is very useful in the context of RFID tags [47]. Finally, additive techniques may be applied, such as screen or inkjet printing, to define antenna, reflector and ground-plane patterns on the garment [32,49-51]. The first screen-printed textile antennas appeared in 2008 [48]. In addition, washable screen-printed textile antennas for 2.45 GHz ISM band [32,51] and for UHF-RFID tags [34] were introduced in 2012. In 2013, it was demonstrated that textile antennas may be inkjet-printed, provided a screen-printed interface layer is first applied to reduce the surface roughness of the textile substrate [49,50]. A particularly interesting recent fabrication technique, first introduced in 2012 [53], consists of applying substrate waveguide technology to create cavities in textile substrate by means of rows of eyelets (Figure ) or by embroidery. This technique leverages the design of wearable antennas with excellent isolation of the antenna radiation from the human body [52-54].

An important issue when designing antennas on off-the-shelf textile fabrics is that the dielectric properties of the materials composing or surrounding the wearable antenna are not readily available. Therefore, dedicated characterization techniques are in order. The problem is complicated by the fact the methods are needed to characterize permittivity and loss tangent of the non-conductive fabrics

together with the sheet resistance or the conductivity of the conductive materials applied to fabricate the antenna. Although conductive and non-conductive parts may be characterized separately, their electric properties may differ when both are combined to fabricate the wearable antenna [20]. This is due to the fabrication (knitting, weaving) and assembling (additional glues or adhesive sheets) processes applied during construction. An accurate prediction of the wearable antenna performance might require simultaneous characterization of all relevant conductive and non-conductive materials by means of test structures that are fabricated in an identical way as the wearable antenna [17]. An additional complication, resulting from the conventional textile production process, such as knitting, weaving and embroidering, is formed by the typical inhomogeneity, anisotropy and instability (in terms of geometry and environmental conditions) of the fabric's material properties [27,44]. A textile fabric may be described as a mixture of fibers, air and water molecules [17,18]. The characterization procedure and subsequent wearable antenna design process will have to cope with these effects.
*Resonance-based characterization* techniques [19], such as cavity and cavity perturbation algorithms, provide accurate anisotropic plain material properties at one or a few discrete frequencies [21]. *Non-resonant* approaches, based on reflection and/or transmission along transmission lines, may yield the dielectric material properties over a wide frequency range, based on a test structure that closely resembles the actual wearable antenna structure [20,31]. Yet, they typically only characterize out-of-plane components, which are the most relevant ones when considering microstrip topologies and when neglecting fringing fields [28]. The wideband material properties found by non-resonant methods may be used as initial values in a second more accurate resonance-based procedure, where narrowband patch antennas are constructed that resonate close to the frequency band of interest [17,22]. These structures also enable to accurately quantify the effects of relative humidity or moisture [16,19,26,35], of compression or strain [29], and of repeated washing cycles on the material properties [32-34,36].

Concerning the material properties of electrotextiles, it is important to note that, due to surface roughness of the fabric, the sheet resistivity at VHF/UHF is significantly higher than at DC [23,32]. Similar to non-conductive fabrics, the knitting or weave pattern will result in different conductivities with respect to the constituent yarns [24,30]. Again, the characterization process may be performed by means of a resonant cavity [24] as well as by non-resonant microstrip transmission lines [23,25,29] and antennas [17] techniques. Special attention must be devoted to a dedicated deembedding procedure that isolates the electrotextile's conductivity from all other effects. Multiple washing cycles might gradually decrease the conductivity of the wearable antenna's conductive parts. This may be avoided by encapsulating the antenna by a breathable thermoplastic polyurethane (TPU) coating [32-34,36,51]. Note that this coating will affect the material properties of the wearable antennas.

## 3. VHF Band Wearable Antennas

In the VHF band, wideband wearable antennas exhibit large physical dimensions that are comparable to the average body size, and they unavoidably are electrically small antennas at the lower frequencies (Figure 1). Typical layouts include double-loop antennas [55,56], dipole-like antennas [57,58] (e.g. bow-tie antennas, folded dipoles, meandered dipoles), normal mode helices (Figure 5a-5d). Indeed, a simple layout, without the need for a multi-layer structure, and ease of fabrication are actually a must when designing physically large antennas that are also required to be suitable for integration into clothing and garments, and robust with respect to wearer movements and harsh environments. Usually, VHF wearable antennas are required to have a dominant vertical polarization and an omnidirectional coverage in the horizontal plane, regardless of the arms positions.

In VHF portable radios, conventional whip antennas mounted on the mobile unit appear as a protruding device outside the human profile, which can limit the wearer's movements and tangle in low-hanging objects. In addition, whip antennas are not suitable for covert operations, and the soldier carrying the antenna is an easily detectable target in battlefield scenarios. Above limitations can be removed by replacing the whip antenna by a helmet-integrated antenna or a flexible antenna integrated inside the clothing in the form of a strip vest or jacket. A vest antenna operating in the 30-80MHz VHF-LB band has been designed, realized and characterized in [55]. It is a flexible double-loop antenna, where one of the two loops acts as a parasitic element. The conductive stripes are integrated with a non-conducting textile that provides mechanical strength and prevents tearing. The antenna is 40cm wide, 20cm thick and its height is approximately 70cm, to match the average size of an adult torso. A whole-body numerical phantom has been used to show the increased safety level of the flexible antenna with respect to a conventional whip antenna, in terms of both SAR and magnetic near-field. However, the measured gain of the vest antenna is about 5 to 10 dB lower than a standard whip antenna. An antenna gain drop at around 70-80MHz has been verified through numerical simulations, as expected due to the well-known body absorption resonance phenomenon at those frequencies [10]. In [56], a flexible double-loop antenna for the Single Channel Ground and Airborne Radio System (SINCGARS, 30-88MHz band) has been realized to show the effectiveness of the narrow woven technology in the development of textile-based wearable electronics. The loops are made of a radiating conductor, which consists of four 0.25in-wide parallel conductive stripes made from tinsel warp yarns and separated by 0.125in-wide insulators of nylon filament yarns.

As far as FM receivers (87-108 MHz) are concerned, large flexible wearable antennas have been suggested as an alternative to tunable small internal antennas. An extensive experimental analysis of the effects of the posture and personal traits of the wearer has been performed in [57], by considering four different dipole-like antennas: a thin half-wavelength dipole, a wide four-finger half-wavelength dipole (Figure 5a), a meandered dipole, and a normal mode helix (Figure 5b). The antennas have been designed to be printed on the inside of a coat and located along the human arms, with the helix wrapped around one user's arm. Conductive parts are made out of a 1cm-wide copper foil tape, and then attached on a 8mm-thick fleece fabric. Each arm of the 10cm-wide half-wavelength dipole is made of four parallel 1cm-wide copper tapes. The shortest antenna is the meandered dipole, which is 80cm long and 23cm wide at most. The straight dipole antennas are both 116cm long, while the helix is about 25cm long and includes a 58-cm long linear counterpoise. It has been found that the human body proximity yields a 15-25% antenna length reduction compared to the free-standing antenna, depending on the size of the wearer (larger reductions have been noticed for bigger wearers, because of an increase of the body effective dielectric constant). The antenna’s performance has been measured by using a local broadcast station as a transmitter (horizontally polarized incident field). To simulate real listening conditions, the volunteers walked, crouched and waved their arms while turning around; meanwhile, the maximum and minimum gains were recorded. The measurements were performed on different persons. However, only slight effects of the wearer physical traits have been noted. The measured maximum gains of the worn antennas are in the range of -13 to -15 dBi. It has been estimated that body losses cause a 3 to 6dB gain reduction (up to 10dB with wearer’s arms hanging down). Null filling in the azimuth radiation pattern was associated to wave diffraction phenomena at the wearer fingertips. Indeed, the human body acts as an antenna platform with finite size and relatively high permittivity. Embroidered versions of wideband folded-dipoles, multi-finger dipoles and bow-tie antennas, all for FM reception, have been studied in [58]. The largest impedance bandwidth has been obtained with a multiresonant antenna made of five folded dipoles connected in parallel (Figure 5c). The body losses help to merge the distinct return loss resonance peaks of the stand-alone antenna, thereby resulting in a wideband antenna. The outer folded dipole is 144cm long and around 10cm wide. The dipole arms are embroidered on a polyester woven substrate, by using a metal composite embroidery yarn (MCEY) made of three strands of Ag-coated copper filaments and three strands of polyester yarns. Radiation properties of the five-folded dipole prototype have been measured with the antenna attached to a jacket and extending from the left forearm to the right forearm, passing over the volunteer’s shoulder. As expected, large variations in antenna gain, pattern and polarization have been noticed when changing the arms’ posture (arms out-stretched, stretched forward or straight down). The gain of the body-worn antenna is in the range of -7 to -16dBd, regardless of the arm movements. The maximum gain is achieved when wearer’s arms are outstretched.

In [59], a flexible fractal antenna (third-order Minkowski fractal geometry) has been designed to operate at 136MHz (Land Mobile Radio systems), by using two different conductive materials, being copper tape and a conductive textile (ShieldIt Super Fabric from LessEMF Inc.). Since the antenna is quite large (around 45cmx60cm) it can only be accommodated on the body torso or back (Figure 5d). A relatively small L-shaped metallic strip (sized as 11cmx18cm) is realized on the same layer as for the fractal radiator, which acts as a metallic counterpoise for antenna tuning.

Simulation results on VHF-band helmet integrated PIFAs (Planar Inverted-F antennas) and PILAs (Planar Inverted-L antennas) have been shown in [60]. The helmet metallic surface is used as the ground plane of the antenna, which occupies a strip all over the semi-circumference of the helmet (a 20cm diameter sphere has been assumed for the head model). Some parasitic elements and a dielectric spacer (with not uniform thickness) between the radiating element and the helmet metallic surface are used to enlarge the return loss bandwidth. Nonetheless, due to the low antenna thickness (only a few cm) the impedance bandwidth is smaller than that required for police and firefighter communications in Japan (146-156MHz). Another narrowband helmet antenna operating at around 150MHz was numerically studied in [61]. The antenna design starts from a strip folded-dipole antenna, which is then curved and accommodated over a hemispherical surface (a dielectric helmet with a 12.5cm radius has been considered in the numerical analysis).

As for the helmet, the human shoulders also represent another “prime location” for wearable antennas, as higher on-body antenna locations improve radiation pattern performance. A shoulder-mountable tunable multi-turn loop was presented in [62], which was able to operate between 150 and 170MHz, with a tunable band of around 1.5 MHz (for a police personal radio communication set). Antenna size is 6.75cmx6.75cm, with a thickness of 1.75cm. The antenna includes a couple of tuning capacitors, and it is attached to a 11.25cmx16.25cm wide counterpoise, which is the smallest size that can be used before a noticeable gain reduction results from body absorption. When compared to a 15cm-long conventional helical whip antenna, the multi-loop antenna exhibits a 3.8dB average gain increase (in the azimuthal plane), at the expense of a narrower bandwidth. Based on extended measurement tests, the authors state that antenna tuning must necessarily be performed when the antenna is on the wearer’s body, due to a significant effect of the human body. Radiation patterns in the horizontal plane have been measured for both the multi-turn loop and whip antennas, for a set of on-body locations and wearer’s postures. It is worth noting that the antennas in [60-62] are narrowband antennas with respect to those in [55-59], as expected since they are electrically small antennas.

## 4. UHF Lower Band Wearable Antennas

For several applications in the UHF lower band, an antenna integrated into clothing represents a valid alternative to small low-efficiency antennas internal to the device/handset or bulky external protruding antennas. With respect to VHF band antennas, the higher frequency allows the implementation of slightly more complex multi-layer antennas (e.g. patches [64,65], slotted and E-shaped PIFAs [71-75,77], meandered slots [76], printed slot/dipole antennas [78], dipoles on thick ceramic substrates [69] or high impedance surfaces [70]), in addition to simpler single-layer dipole-like antennas [63,66-68] (Figure 6a-6e). Wideband wearable antennas for DTV reception have been realized by resorting to wideband dipole-like and slot-like layouts [81-88], while most of the solutions proposed for wearable narrowband miniaturized antennas at 406 MHz are dipoles with spiral-shaped arms [89,80] or meandered dipoles [91-94].

### 4.A Wearable antennas operating up to around 600 MHz, for personal and professional mobile radio systems

In [63], a strip dipole antenna (67cm long and 7.9cm wide) operating in the 220-370 MHz frequency band was optimized to yield optimal performance (in terms of impedance matching and azimuth-plane pattern uniformity) when mounted on a human shoulder (one dipole arm is at the front side and the other arm is at the backside). The metallic geometry of the dipole arms (partitioned in squared surface pixels) has been optimized through a genetic algorithm, in presence of a numerical body phantom. A homogeneous dielectric phantom with muscle permittivity is used, with a 1cm gap between the metallic strip and the model surface. Different from conventional wearable UHF dipole-like antennas, the optimized antenna does not exhibit nulls in the horizontal-plane pattern. Another antenna that can be worn as a strap over the shoulder has been suggested in [64,65]. It operates at the 380-390MHz band. The conformal multi-layer (grounded) low-profile antenna is made of two adjacent half-wavelength long patches that are strongly coupled by a narrow slot (Figure 6a). The patches are excited by a folded dipole centered on the top of the slot. Foam dielectric is used as a substrate and the conducting parts are made out of a copper tape. The total size of the unfolded antenna is 790mmx50mmx5.6mm. Antenna folding around the shoulder determines two null-directions in the azimuth-plane radiation pattern (null directions are parallel to the body torso).

In [66,67], a conformal asymmetric meandered flare dipole for communications at 300MHz has been realized on a flexible 0.1mm thick FR4 substrate (Figure 6b), without metallic backing. Only one arm of the dipole is meandered, as the other one is used to accommodate a balun. The dipole length is close to 30cm, and its width is less than 4cm. Measurements were performed with the antenna mounted on the center of the torso area of a plastic mannequin filled with a human tissue equivalent liquid. The flare dipole exhibits a measured bore-sight gain close to -15dBi at 300MHz, which can be increased by leaving some space between the antenna and the phantom shell. Indeed, a

5dB increase in simulated gain was noticed when moving the antenna from 0.25 to 1.25cm away from the body model. An embroidered version of the asymmetric meandered flare dipole in [67] (operating in the 500-600MHz band) has been realized by using highly flexible conductive fibers [68]. Silver-coated Zylon fibers have been used to embroider the dipole geometry onto a polyester fabric by using a digitally controlled embroidery machine. Double-layer embroidery was chosen to minimize physical discontinuities and achieve a high stitching density, thereby increasing the conductivity of the embroidered surface. A -5dBi peak gain was measured with the antenna worn on a human phantom torso. It has been shown that electrical performance of the embroidered flexible dipole is comparable with that of its printed counterpart, with also satisfactory mechanical properties.

Some interesting wearable antenna solutions are those exploiting the thickness and material properties of some protective inserts that are included in typical armored vests for law-enforcement personnel and soldiers. In [69], a set of dipole antennas operating in the 225-450MHz band have been designed to fit on the hard ceramic reinforced (bulletproof) plates of the Improved Outer Tactical Vest (IOTV) body armor (Figure 6c). Measured relative permittivity of the ceramic plates is larger than 10, thereby enabling antenna miniaturization. Asymmetric dipoles were chosen as they provide a wider impedance bandwidth compared to center-fed dipoles, by exciting another resonant mode adjacent to the fundamental mode. The dipole shape was optimized to exploit the maximum area of the armor ceramic tiles: 16cmx20cm wide for the side plates, 23cmx31cm wide for the front/back plates. In [70], a high impedance surface (HIS) has been integrated into the multi-layer structure of an armor vest to improve return loss performance of wearable grounded dipole-like antennas (where the metallic ground in added to limit wearer RF exposure and increase antenna efficiency). The design was carried out at the 400MHz TETRA frequency band (TETRA - TErrestrial Trunked Radio - is the personal communication system used in Europe for police and emergency services). The structure of the HIS is as follows: the frequency selective surface consists of an array of 15x15 interwoven spiral elements (23mm is the side of the unit cell). The HIS is mounted on top of a 1cm armor coating made of a layer of Aramid fibers and a layer of interwoven metallic threads, which are used as the dielectric substrate and the ground plane of the HIS, respectively. To show the advantages of the HIS, a 28cmx6cm dipole was designed to operate on the HIS surface. Both the dipole and the frequency selective surface were printed on a thin Mylar layer, and are separated by a 1cm thick denim layer.

A shoulder-mountable low-profile PIFA has been proposed in [71,72] to realize a narrowband antenna for police and fire service radios at 350MHz, to be used separately from the radio unit (Figure 6d). Antenna size is 5cmx5cm, with 1cm thickness. The conducting element is printed on a 0.6mm thick dielectric layer, and an air gap separates it from the ground plane. Tuning is achieved with a capacitor between the feeding point and the coaxial connector. Moreover, a few slits on the conducting element help to lower the resonance frequency. A discussion is added to show how a ground plane, which is 5cm wide and almost 20cm long, can effectively reduce radiation performance degradation due to the leakage currents on the external surface of the cable’s outer conductor (the latter being a typical issue in low-frequency antennas with a small ground plane). Actually, in order to make the antenna conformal to the human shoulder, the flexible ground plane is made of two thin stainless plates (0.05mm thick and 7cm long) that are attached at two opposite sides of the shorted-patch ground plane. A prototype mounted on a human shoulder achieves a -5.5dBd gain, which is 3.5dB higher than the gain of a conventional 21cm-long whip antenna (azimuthal average gain is -8.1dBd). Measurements on a worn prototype demonstrated that the antenna input impedance is robust with respect to the body presence, while antenna gain can be optimized by controlling the distance of the antenna from the human shoulder and head. The shoulder-mounted PIFA antenna was used as a receive antenna during a measurement campaign in a real multipath propagation scenario (a route around 20m-high buildings) [72]. The average received power was 4-5 dB higher than that of a whip antenna carried in a chest pocket. It was noted that above result was in agreement with the difference between the measured average gains of the two antennas.

A low-profile printed E-shaped PIFA (Figure 6e) has been designed in [73] for the 380-400MHz band of the TETRAPOL system for undercover operations (TETRAPOL is a digital, purpose-built PMR- professional mobile radio - technology for mission-critical public safety users). The low-profile structure allows the antenna to remain unseen when covered by a layer of clothing (low visual signature) and to be more unobtrusive than a whip antenna. The antenna has been designed to cover a bandwidth larger than the nominal one, in order to remain still operational when covered by wet clothing, mud or snow, or when the body-antenna distance changes due to the body movements or to the unpredictable thickness and properties of the clothing under/above the antenna. Wideband features are achieved through two slightly asymmetric arms that introduce closely spaced resonances. Additionally, a resistor is connected at each radiating arm (between the metallic radiator and the ground plane) and a matching impedance network using SMD components is inserted at the antenna input. The radiating element is 14cmx22cm large, and a 2cm-thick layer of Rohacell separates it by a 30cmx30cm ground plane. In spite of the losses introduced by the two resistors, the E-shaped wearable antenna exhibits a measured gain of -12dBd, when it is mounted on the body lumbar region.

A flexible version of the E-shaped PIFA in [73] has been realized by using a thin copper layer for the shorted patch (12cmx19cm wide) and a conductive non-woven fabric for the 30cmx30cm ground plane [74]. The two conductive layers are separated by a 15mm-thick foam material commonly used in orthopedics, as it is flexible, exhibits low dielectric losses and does not absorb moisture. The authors noted that bending the flexible E-shaped PIFA can improve impedance matching with respect to its planar printed version. The flexible E-shaped PIFA exhibits a reasonably omnidirectional pattern in the azimuthal plane, with an average gain of -12dBi, when mounted on the human body.

In [75], a dual-resonance feature has been added to a modified PIFA layout to get a wide bandwidth around 430MHz, with a reduced thickness with respect to a conventional layout. The shorted patch (15cmx13.7cm) is on a 25cmx25cmx0.8cm substrate. Due to the large size of the antenna, textile material selection results from a trade-off between the flexibility and robustness requirements. Indeed, an adequate antenna rigidity is needed to limit the bending and crumpling deformations induced on large antennas by the wearer movements. Such a goal was obtained by using EVA (ethylene-vinyl acetate) foam as a substrate, and copper gauze to realize the antenna conducting parts. Copper gauze allows soldering and can be sewn on the EVA substrate with regular cotton thread. Around 1.5dB gain loss was measured when the antenna was attached to a cotton cloth and worn by a person (2D measurements were performed in an anechoic chamber).

A printed meander line slot operating at 430MHz has been realized and tested in [76]. To realize a compact antenna, the slot line is terminated by a short circuit close to the feeding point (as in PIFA layouts). Moreover, the meandering produces a longer current resonant path within a reduced space. The antenna is fed by a coplanar waveguide (CPW) feeding line to achieve a single-layer implementation (with no ground plane). The overall size of the antenna prototype is 11.5cmx7.5cm, and it has been realized on a 1.6mm thick FR4 substrate. The antenna has been tuned and characterized without accounting for the body presence. However, to obtain a wearable version with a low antenna-body coupling, an EBG (Electromagnetic Bandgap) surface has been suggested, as an alternative to a ground plane or a reflector element. Indeed, the latter solutions are not effective for electrically small antennas. The authors noted that a miniaturization of the periodic cell is mandatory to implement an effective shield for an electrically small UHF-band wearable antenna (as it was also done to realize the frequency selective surface for the HIS in [70]). The PIFA in [77] has been realized on a 4mm-thick fleece to operate at around 400MHz. Bandwidth requirements are met by resorting to slots realized on both the radiating element (12cmx3.5cm) and the ground plane (25cmx8cm). A power-flow analysis has been reported to study the body-coupling effect as a function of the patch position with respect to the slot in the ground plane. In [78], a set of linearly polarized and dual-polarized printed antennas have been designed and characterized when the antennas are mounted on the human body, for radio links at 434MHz. Among them, a printed loop with a 5cm diameter, a dual-polarized dipole/slot printed antenna (26cmx6cmx0.16cm) and its folded version (7cmx6cmx0.16cm).

A circularly-polarized helmet antenna that covers the 243-317MHz band of the Mobile User Objective System (MUOS) for narrowband tactical satellite communications, has been designed and tested in [79]. The semi-conical asymmetrical antenna is a two-turn two-arm Archimedes spiral antenna. The spiral is encapsulated into a 1.5cm thick nylon shell that fits over a standard Kevlar helmet. The purpose of the nylon surrounding the spirals is two-fold. It protects the antenna and holds the spiral in the proper shape. In addition, its high relative permittivity (around 4.3) increases the antenna electrical length. A helmet antenna experiences a little interference from the wearer's body and equipment as body, head and shoulders help to reduce back radiation toward nadir direction. In [79], human head and shoulders increase the F/B ratio by 3dB, but the half-power beamwidth decreases from 120 to 90 degrees. Also, the asymmetrical configuration (the spiral turn at the top of the helmet has a different pitch with respect to the lower spiral turn) helps to increase the F/B ratio (zenith-to-nadir ratio). If more space at the lower part of the helmet is available, a further F/B increase can be obtained by adding a reflector ring acting as the reflector element of Yagi-Uda antennas. SAR levels and body effects on the antenna parameters have been analyzed using a numerical phantom model.

A half-wavelength semi-circular loop antenna operating at 449MHz has been proposed to be integrated onto the visor of a worker helmet [80]. The loop has been realized through a series of meanders, to fit the antenna onto the helmet visor. The antenna size is 7cmx3.6cm, and a thin copper ground plane is realized inside the helmet.

It is worth noting that radiation pattern and polarization of a helmet antenna are quite stable with respect to body postures and movements, as the head is generally held upright (*i.e.* a more stable radio connectivity is guaranteed regardless of the wearer's body movement and orientation).

### 4.B Wearable Antennas for DTV mobile receivers

Wideband wearable antennas for digital television broadcasting (DTV) reception have been proposed as an alternative to small tunable antennas integrated into the portable electronic device (Figure 7a-7c), by taking advantage of the larger room available on the body surface. In [81], a T-shaped slot antenna and a T-shaped planar monopole have been designed for DTV signal reception in the 470-770 MHz band (Figure 7a). The T-shaped planar monopole includes parasitic L-shaped elements to improve return loss at the higher frequencies, and its overall size is 40cmx15cm. The T-shaped slot antenna with arrow head is etched on a metal surface whose size is 24cmx12.5cm wide. Starting from the T-shaped monopole in [81], an antenna with a larger bandwidth has been developed, to accommodate return loss variations due to antenna curvature, user's body presence, and deviations in textile substrate thickness and permittivity [82]. A prototype has been fabricated using felt and a conductive textile (Nora, from Shieldex Trading, Inc.). Despite the large size of the antenna, its impedance bandwidth does not change significantly when the antenna is crumpled, attached to the human chest or rolled around the arm.

The flexible wearable antenna for DTV reception in [83] is a dipole antenna where each arm has a triangular shape, and the feeding port is at a point along two sides of the triangles that are parallel (Figure 7b). The antenna is realized with a flexible conductive fabric attached to a rectangular common fabric. The overall size of the antenna is around 25cmx25cm. To allow a fast and simple antenna connection, a pair of snap buttons for dressmaking has been used. Snap buttons are attached to the conductive fabric by thread, and to a PCB board by soldering. Measured antenna gain is around a few dB below zero. The wideband characteristic of the prototyped antenna allows its use in a larger bandwidth (379 to 990 MHz), such that it can be used for other wireless communication systems, being mobile phones at 800/900MHz and personal mobile radios at 422MHz. A DTV antenna made of a rectangular metallic plate with an L-shaped slit has been designed to be located in the wearer's neck back (hood-type antenna) [84]. A prototype has been realized by using highly conductive fabric and it is 5.7cmx23cm large. The triple-loop antenna in [85] has been realized with a conductive fabric attached on a dielectric cloth. The three nested square-shaped loops have side size equal to 17.8cm, 12.1cm and 9.4cm, respectively. However, the antenna design needs improvements to meet return loss specifications when it is worn on the human body. A notched planar monopole (8cmx8.5cm wide) has been designed in [86], which is suitable to be mounted on the user's head. Indeed, the monopole ground plane is a 3cm-wide curved metallic strip that looks like a headband to support the antenna structure. It is worth noting that the monopole is perpendicularly oriented with respect to the metallic strip and head surface.

The dual-band flexible textile antenna in [87,88] covers the DTV band along with the frequency bands of a number of wireless communications standards: GSM850/900, UMTS-LTE, WLAN 2.45/5.8GHz, WiMAX 3.5 GHz, Hiperlan 5.2 GHz. The antenna is a square-shaped monopole fed by a microstrip line with a rectangular ground plane (Figure 7c). Antenna size is around 11cmx24cm. The antenna is made of felt and Nora conductive textile. The monopole and the ground plane are attached on the opposite side of the felt layer. A satisfactory return loss performance is also guaranteed when the antenna is mounted at various positions on the human body, even when covered by a number of different garments or bent around the arm. However, it is worth noting that efficiency measurements in an anechoic chamber have shown that antenna efficiency decreases by up to 90% when the antenna is mounted on a phantom surface. The efficiency can be improved by interposing an additional felt layer between the antenna and the body surface.

### 4.C Wearable antennas for Search and Rescue Systems

In 2009, the frequency of operation of all Search and Rescue (SAR) beacons (*e.g.*, Personal Locator Beacon, PLB, and Emergency Locator Transmitters, ELT) was fixed to 406MHz [89,90]. In this context, wearable antennas can be useful to improve the efficiency and robustness to unintentional accidents of PLBs. A compact antenna has been obtained by using a right-hand circularly polarized (RHCP) crossed-dipole [89], whose arms are convoluted into spirals to reduce antenna size (the spiral is 73mm wide). The dipole is fed through a microstrip line that is electromagnetically coupled to the spirals. In a first prototype, a printed crossed-dipole was fabricated on a thin dielectric substrate and then pasted on a felt substrate using non-conducting tape, while a copper sheet was used to realize the antenna ground plane. Later on [90], an embroidered textile version of the above CP antenna has been realized and used to test the antenna return loss under bending conditions, as well as in water proximity. More recently, a two-antenna system using two grounded folded meandered dipoles has been designed and tested in [91]. Both dipoles are 30cm long. The dipoles are mounted onto the floating elements of a commercial life jacket, in the front and neck sides, in order to radiate complimentary radiation patterns by switching between the two antennas during the transmission intervals. The ground plane is realized by a conducting foil attached to the opposite side of the floating element, at 9cm (around 1/8 of the free-space wavelength at 406MHz) away from the dipole, which corresponds to the thickness of the floating foam material. The ground plane shielding effect achieves a very stable antenna performance with respect to the wearer’s movements and water vicinity. A statistical analysis of return loss measurements has been introduced, for a meaningful characterization of the fluctuations induced by random wearer’s movements. The proposed antenna configuration exhibits stable performance from both the electrical and mechanical point of views.

A radiator made of two orthogonal meander dipoles has been designed to provide a dual-band antenna for PLBs at 406MHz and military communication systems for broadcasting at 850MHz, respectively [92]. The dipoles are made of copper tape, and different textile materials have been tested as antenna substrates (jeans, Policot, Polyester). Since above textile materials have similar electromagnetic parameters, comparable numerical results have been noted. Finally, two compact antennas integrated on an inflatable life jacket have been designed and tested in [93], for operation with a commercial COSPAS-SARSAT user terminal. A shorted-patch antenna (28.3cmx6.5cmx1.75cm) radiates at 406MHz, while a meandered dipole (29.7cmx3.3cm wide) with a ground strap is designed to operate at 121.5MHz.

## 5. UHF Band Upper Wearable Antennas

Generally speaking, at the UHF upper band frequencies (roughly, when free-space wavelength is between 30cm and 50cm), the human body looks like a moderately (electrically) large platform, thereby allowing for the positioning of high-efficiency antennas that include an effective ground plane whose size can be comparable or even larger than the free-space wavelength. Nonetheless, compact antennas with a size of the order of a quarter-wavelength can also be used without sacrificing too much antenna efficiency. Most of the antennas described in the following subsections are for personal short-range communications at around 800MHz [94,95,97-103], and bodyworn transponders for identification, tracking and sensing at 860-960MHz [108-142].

### 5.A Wearable antennas for the 868MHz ISM band and contiguous bands

Wearable antennas for BAN radio links in the 868MHz ISM band and contiguous bands have been realized with either a single metallization layer [94,95,104], or a multi-layer grounded structure [97-103] (Figure 8a-8c).

A log-periodic array of wire folded dipoles has been proposed in [94] to realize a wideband textile antenna operating at around 868MHz. The suggested “practical design approach” consists in designing a free-space antenna that is well matched over a bandwidth much larger than that required, so that the antenna can still operate when worn by the user. Since the array of folded half-wavelength dipoles exhibits endfire radiation, it is suitable to be located on the human upper arm or shoulder. An array of two folded dipoles has been made out of copper tape, and attached to the shoulder of a cotton shirt. During measurements, the antenna was draped over a balloon filled with salt water to mimic the human torso. Another balloon filled with salt water was positioned on top to mimic the human head. A 2.4 GHz embroidered version of the two-element array was also realized and tested. Short circuits in the dipole arms and a parasitic dipole (either folded or not) are suggested as antenna tuning options, as an alternative to folded dipoles with arms of different radius. Indeed, the latter approach, which is typical for wire folded dipoles, could be difficult to implement in an embroidered antenna. The dual-band spiral-shaped monopole printed antenna in [95] operates in the SRD (Short Range Device)/868MHz and 2.4GHz ISM bands. A CPW feeding with a ground layer on the same level of the metallic rectangular spiral (single layer metallization) makes the antenna suitable for integration onto textile fabric. An antenna prototype on a 0.78mm thick FR4 substrate has dimensions of 4.1cmx3cm. Simulated input impedance does not change significantly when the body-antenna distance is larger than 3mm. The robustness of the antenna input impedance with respect to the body proximity is investigated through the numerical analysis of the amplitude and direction of the instantaneous Poynting vector evaluated on the antenna surface. Simulation results at 870MHz show that the body-worn antenna radiation efficiency increases as the separation distance with the body decreases. To justify that unexpected behavior, the authors state that, at the lower band, the printed spiral-shaped monopole antenna behaves as an electrically small antenna, and then the radiation (or reflection) from the body may dominate over the radiation from the antenna itself, thereby determining a radiation efficiency increase [96].

By using high permittivity ceramic substrates, two compact narrowband antennas have been designed to operate at 868MHz [97]: a coaxial-fed patch and a PIFA. The size of the circularly-polarized patch (single-feed square patch with truncated edges) is smaller than 3cm, and the substrate thickness is only 2mm (the relative permittivity of the ceramic substrate is 38). The size of the PIFA is smaller than 3cmx2cm. The dielectric layer is 1.9mm thick and exhibits a relative permittivity equal to 10. For both antennas, the ground plane is only 1mm larger than the radiating element, to achieve an almost omnidirectional pattern. The conducting parts of the prototypes have been realized by using adhesive copper foil. Another miniaturized antenna for BANs at 868MHz (a button-shaped PIFA) has been realized on a magneto-dielectric substrate, namely a barium-strontium hexaferrite disc [98]. The measured magnetic and dielectric relative permittivity  of the synthesized material are equal to 2 and 12, respectively. The 19.15mmx17.65mm patch (4μm thick silver film) is realized on a 5mm-thick circular disc of the magneto-dielectric material, which has a 33mm diameter (Figure 8a). The circular shape of the substrate has been chosen to avoid sharp edges in the wearable antenna realization. To improve broadside radiation and reduce body effects, a shielding conductive fabric has been attached to the patch ground plane.

A compact and flexible textile PIFA has been designed to operate at 860MHz, for integration onto a jacket sleeve [99,100] (Figure 8b). The antenna was designed to be used by emergency personnel for location monitoring and data transmission. An electromagnetic coupling between the patch and the microstrip feeding line avoids soldering. Threads made of silver plated polyamide filament yarns have been used for the antenna conducting parts, while a thick padding has been used for the substrate. A shorting pin is located at the patch center and the maxima of the radiation patterns are in the plane parallel to the antenna, so resembling the characteristics of higher-order mode microstrip patch antennas suggested for on-body communications. The patch size is 40mmx40mm, over a square ground plane with a side 10cm wide. A larger rectangular patch (146.5mmx126.5mm) was designed to operate at around 832MHz [101]. Patch and ground plane are made of a copper foil pasted on Bakhram textile substrate (measured relative dielectric permittivity equal to 2.03).

In [102], a slot-coupled shorted patch antenna operating at the 902-928MHz band has been designed to be combined with flexible solar cells, to realize a compact wireless node for body-centric communications (Figure 8c). The antenna substrate is a flexible polyurethane foam, while the feed substrate is constructed by assembling two aramid textile layers typically used as an outer layer in firefighter jackets. The conductive patch (6.2cmx8cm large) and the ground plane (12cmx12cm) are made of a copper coated nylon fabric (Flectron), while the feeding line is constructed by using copper foil. Antenna thickness is around 12mm. A maximum gain of 1.6dBi for the on-body antenna has been measured in an anechoic chamber.

Although not appropriately related to off-body wearable communications, it is interesting to mention a patch with a U-shaped slot that has been designed to be integrated between the textile layers of a mat, for detecting heartbeat signs of a patient during medical scans [103], at 868 MHz. The patch antenna (3.5cmx3.5cm) is printed on a 8mm thick Teflon layer (substrate size is 4.9cmx7.6cm). The patch was designed by assuming free-space operation. Experimental results showed that, in operating conditions, the resonance frequency of the patch deviates significantly from the design frequency of 868MHz. This was an expected result since, when the patient lies on the mat, the antenna is at a distance of a few mm from the body surface and the patch radiates toward the body (namely, the patch ground plane does not work as a shield between the body and the radiating element).

In [104], a dual-band CPW fed monopole whose shape is optimized through genetic algorithms has been proposed for soldier communications in the 750-870MHz and 1350-2700MHz frequency bands. A prototype has been realized on a thin curved dielectric Kevlar substrate, with the final goal of integrating the antenna between the layers of a ballistic helmet comprised of aramid fabrics impregnated with polyvinylbutyral (PVB) modified phenolic resin. Conducting ink printing technology was investigated to realize the antenna metallic parts.

A recent new application in which wearable antennas will play a key role is the harvesting or wireless transfer of RF power from a source to a body-centric device [105,106]. A textile antenna comfortably integrated in a garment can provide a large harvesting aperture, enabling the use of UHF frequencies that suffer from lower path loss compared to microwave frequencies. In [107], a wearable UHF rectenna is proposed operating in the frequency range 860–918 MHz. A maximum conversion of about 50% is obtained at 876 MHz, for an incident power density of 14 W/cm$^2$.

### 5.B Wearable antennas for UHF-RFID transponders

Radio Frequency Identification (RFID) technology at the UHF band is widely applied for the automatic remote identification through radio waves, in logistics, warehouse and supply-chain management, access control, etc. Labeling of textile products through UHF RFID tags has been applied for inventory management and anti-counterfeiting in fashion retails, as well as for garment and sheets traceability in industrial laundries. As an alternative to RFID tags embedded into or printed on clothing paper-labels, flexible textile tags can be directly integrated into either the textile label or the clothing fabric. In above applications, a short read range (up to a few tens of cm) is usually required and tag reading is performed when the clothing is not worn by a human. Then, main design concerns are about the tag lifecycle and its robustness to washing cycles, textile stretching and chemical agents. Longer read ranges are required when the RFID tags are used as low-cost wearable sensors for remote monitoring of vital signs and activities of a person, as well as for imperceptible identification, monitoring and tracking of patients in hospitals, elderly at home, and workers in dangerous working areas. In those applications, tag performance degradation due to the antenna operation nearby the human body is also of extreme interest, and body effects (antenna detuning, tag mismatching losses and body power absorption) need to be mitigated. It is worth to mention that the RFID tag antenna input impedance has to be conjugate matched to the IC input impedance (different from $50\,\Omega$) to ensure an adequate power transfer to the tag microchip, which exhibits an ohmic-capacitive impedance.

The 840-960MHz band includes most of frequency bands assigned to UHF RFID applications worldwide. Above all, it is worth mentioning that, thanks to the relatively high frequency, the tag dimensions (typically less than 15cm) easily match the maximum-size constraints for wearable antennas. Often, tags are so small and flexible that bending effects are negligible (see wristband tags, for example). Also, it has been verified that a separation of the tag antenna from the body surface larger than 1cm suffices to reduce detrimental body effects. In this context, several single-layer (with no ground plane) and multi-layer grounded antennas have been designed and tested, when they are mounted on the human body or on a body-phantom surface (by often adding system-level measurements to antenna characterization) [108-142]. Some of them are grounded printed antennas belonging to the class of the low-profile platform-tolerant tag antennas [109-121]. Indeed, in the UHF RFID band, an effective shielding ground plane can still be small enough to allow antenna positioning on the wearer's torso/back or upper arm. For instance, in [109-113], a set of grounded printed antennas with one or two dielectric layers have been studied to realize RFID tags suitable for people identification in mass races and workplaces (in the sense that the tag must be suitable for integration on name-badges or runner number labels). A conventional half-wavelength rectangular patch (74mmx165mmx4.8mm) realized with a conductive fabric on a flexible and lightweight foam dielectric was able to give a 5dBi gain, when the antenna prototype was mounted on a body phantom [109]. A more compact layout consists of a 3-arm folded dipole printed on a 0.24mm thick dielectric layer and placed over a 2x2 array of grounded sub-wavelength rectangular patches [112]. The four patches are printed on a 1.82mm-thick high permittivity dielectric ($\varepsilon_r$=10), and the antenna size is 70mmx105mm (on-phantom measured gain is 0.6dBi). To avoid using high permittivity dielectrics, a layout made of two slot-coupled shorted patches (namely, two quarter-wavelength patches separated by a gap and shorted to the ground at the opposite edges) that are excited by a meandered dipole has been proposed in [113]. The dipole is printed on a thin dielectric layer and placed on the patch top surface. The antenna overall size is 60mmx95mmx1mm, and the dielectric permittivity is 3.2. A further simplification is obtained by exciting the slot-coupled patches directly at the slot between the inner patch edges, so avoiding the need for the printed dipole [113] (Figure 9a). The antenna size is

60mmx100mmx0.76mm. For the last two antennas, the measured gain is close to 1.6dBi, when the antennas are mounted on an agar phantom. An antenna made of two slot-coupled shorted-patches as in [113] was also presented in [114]. The antenna is 40mmx116mm wide. The patch substrate is 0.4mm thick, and the antenna is placed on a 1.4mm thick foam layer. It is worth noting that in [113] two additional thin slots are used for the antenna tuning. More recently [115], a wideband version of the antenna in [113,114] has been obtained by introducing on the patch top surface a loop delimited by a 1mm-wide slot pattern (thereby increasing the number of geometrical parameters available for best antenna tuning on a wide frequency band). The antenna is 32mmx137mm wide, and it is realized with a 1.57mm-thick Rogers RT5880 substrate ($\varepsilon_r$=2.2). Examples of quarter-wavelength shorted patches can be found in [110,116]. The shorted patch in [116] is made out of a copper foil attached onto a flexible and soft foam substrate (antenna thickness is equal to 3.2mm). The 30mmx79mm shorted patch is attached on a 200mmx200mm silver fabric sheet to further decrease the antenna-body coupling. In [117], a quarter-wavelength shorted patch excited through an H-shaped slot has been suggested as an antenna for a wearable tag to be used for tracking of human movements in indoor environments (Figure 9b). Two different prototypes have been realized, whose overall size are 60mmx90mm and 60mmx60mm. The Teflon substrate thickness is 4mm, and a thin adhesive PVC film has been used to isolate the antenna from the body. A miniaturized version of the antenna in [117] has been obtained by adding some additional slots onto the patch element [118,119]. The shorted patch size is 45mmx35mm and it was made out of an adhesive aluminum sheet. A 3mm-thick EPDM (Ethylene-Propylene Diene Monomer) foam was used as a substrate (relative permittivity equal to 1.21).

A meandered printed planar monopole (126mmx156mm) has been realized on a 3mm-thick grounded FR4 layer [120]. In the same paper, a smaller slot-version layout (30mmx120mm) has also been designed, on a 1.27mm-thick FR4 grounded layer. Thin tag antennas realized with either printed meandered dipoles [110] or multi-arm folded dipoles [109] have shown unacceptable performance when backed by an adjacent metallic shielding. In theory, a dipole backed by an artificial magnetic conductor (AMC) could be used to realize thin wearable tag antennas. However, AMCs are usually complex multi-layer periodic structures, which can strongly limit flexibility and ruggedness of the final tag antenna. As an attempt to face with above limits, a flexible AMC realized by an inkjet-printed EBG surface on a metallic ground plane has been suggested in [121]. A 3x2 array of inkjet-printed split ring resonators is realized on a paper substrate (overall size is 120mmx90mm), and a 3mm-thick foam fills the gap between the EBG surface and the ground plane. Then, an inkjet-printed dipole antenna is located on the top of the EBG surface, at a distance of 3mm.

Low-profile single-layer printed antennas including a specific material slab instead of a metallic ground plane can also be used, if antenna impedance is optimized by accounting for the body proximity and provided antenna gain reduction due the body power absorption can be tolerated. In [122], a suspended metallic square patch with a nested H-shaped slot has been designed to guarantee the best matching performance when the suspended patch (with no ground plane) is isolated by the body surface through a 4mm-thick silicon layer with a relative permittivity of 11.9. The patch size is less than 60mm. In [123], a flexible magnetic composite (BaCo ferrite-silicone composite) has been proposed as a 1.3mm thick substrate of a T-matched meandered dipole, to realize a conformal and compact wristband tag (66mm long and 19.8mm wide). It is worth noting that in the latter case the RFID antenna design was performed at 480MHz.

As far as textile tags are concerned, embroidered T-matched dipoles and simple straight dipoles have been used to check the effect of different stitch and thread densities, as well as sewing patterns, on the read range of a free-standing tag [124-126]. Prototyped straight dipoles and T-matched dipoles are 170mm and 130mm long, respectively. It was verified that sewing pattern has to be chosen in such a way that the conductive threads are aligned with the direction of the current flow along the antenna, while higher thread density improves the tag performance slightly. A similar analysis for various free-standing embroidered tag antennas was also presented in [127-129]. Flexible tags based on a 120mmx9mm T-matched dipole [127], a YJ kindergarten logo [128], and a 130mmx37mm antenna by the shape of “RFID” alphabetic characters [129], where realized by using twisted electro-threads and characterized (in free-space) in terms of antenna return loss and tag read range pattern. In [130], several electro-textiles have been considered to realize the 150mmx90m ground plane of a rectangular patch (the patch is made of copper on a 3.175mm thick Rogers RT/Duroid substrate). Read range performance for six embroidered ground planes, with different thread densities and sewing patterns (Shieldex electro-threads and cotton fabric have been used), and four LessEMF conductive fabrics (copper polyester taffeta fabric, argenmesh fabric, ripstop silver fabric, and stretch fabric), have been compared with those achievable by a conventional copper ground plane. Embroidered structures exhibit a larger bandwidth when compared to conductive fabrics, due to the lossy conductive threads. Also, it has been noted that the elastic structure of the stretch fabric determines a downshift of the patch resonance frequency. It is worth noting that complex antenna topologies developed for high-performance printed circuit antennas are not suited to be realized with conductive textiles or embroidered metallic yarn, and simpler configurations are usually preferred.

Experimental studies of the body proximity effect on the read range of embroidered T-matched folded dipoles can be found in [131,132]. In [131], the dipole size is 77mmx39mm and it was realized with a conductive silver thread on cotton fabric, under which Buckram fabric was used for supporting the stitching as well as to increase the distance from the body surface. The read range vs. direction around the wearer’s body has been measured in a shielded EMC chamber. In [133], measurements with a ring-ended dipole were performed for different separation distances of the tag from the body (Fleece fabric was used to fill the gap between the antenna and wearer’s body), and for a set of on-body antenna locations. The dipole was made of a copper tape on fabric and its size was only 7cmx2cm. Thanks to its small size, it can easily fit in shirt collars and cuffs. Read range pattern measurements for different on-body antenna locations have shown that the upper arm and wrist locations exhibit the largest read range and the best pattern omnidirectionality, respectively.

The impact of moisture absorption and repeated washing cycles on the performance of an embroidered tag has been experimentally studied in [134], where a T-matched dipole has been used for the tag antenna. The dipole was made of a conductive thread (silver plated polyamide filaments, from Shieldex), whose mechanical strength allows for a standard embroidery fabrication on a cotton fabric. The IC was connected to the embroidered dipole using conductive epoxy. It has been verified that moisture absorption determines a temporary reduction of tag read range. Indeed, due to the water absorbed by the cotton, antenna efficiency reduces and antenna input impedance changes, and both of them determine a reduction of the antenna realized gain. On the other hand, washing operations determine permanent performance reduction, which accumulates over the washing repetitions. The rapid read range reduction after each washing repetition and the permanent degradation have been attributed to the dissolution of conductive material from the antenna threads. Flexible and hydrophobic coatings of both antenna and IC can be realized by using thermoplastic polyurethane (TPU) or polydimethylsiloxane (PDMS) [135,136]. Indeed, PDMS polymer is a soft, hydrophobic, heat-resistant and flexible material. Polymer-ceramic composites have also been suggested, which could provide durability and miniaturization at the same time [137]. In [138], a Parylene layer has been tested as a waterproof coating for a dual-band (900MHz and 2.4GHz) inkjet-printed 100mmx90mm wide monopole antenna on paper substrate.

To avoid the critical electrical joint between the textile antenna and the IC, and to improve tag resistance to laundry cycles, a microchip including a small loop can be inductively coupled to a larger textile antenna, and then the two parts can be joined together through a lamination process using TPU as encapsulation material [139]. In [140,141], the chip is connected to a small loop (loop perimeter less than $\lambda/10$), and they are packaged together. Then, a wideband logarithmic meander line antenna made of ThN30 electro-thread is magnetically coupled to the loop. ThN30 is a multifilament conductive fiber composed by one hundred inox fibers coiled by a nonconductive duct. The log-periodic antenna was sewn on a 82mmx25mmx0.24mm piece of polyethylene.

In the context of passive RFID-enabled sensors, the potentials of an embroidered T-matched dipole to implement a strain sensor have been experimentally investigated in [142]. The 150mm long dipole is embroidered with an electro-thread, on a polyester-based stretchable fabric.

## 6. VHF/UHF Wearable Multi-Antenna Systems

In some applications, a single wearable antenna cannot provide the required multiband/wideband spectral coverage or omnidirectional spatial coverage, therefore multi-antenna arrangements have been proposed. Multi-antenna systems are mandatory when the antenna topology includes a reflector (to reduce SAR or increase antenna gain, or both) that limits the antenna angular coverage, whereas an omnidirectional pattern is required. Also, in the UHF band, the azimuth plane radiation pattern is significantly distorted by the body shadowing effect. Finally, multiple antenna systems for implementing reception diversity schemes and MIMO (multi-input-multi-output) techniques in wearable personal communication systems can reduce the multipath fading effects induced by wave propagation in rich multipath scenarios and wearer’s random movements.

### 6.A Multi-antenna systems for wide spatial coverage

Body shadowing and antenna elements acting as a reflector/shield can introduce low-radiation sectors in the antenna radiation pattern. If an omnidirectional pattern is required in the azimuthal plane, multiple antennas can be located around the body and their signals properly combined. Pattern diversity schemes, phased arrays, switched beam antennas are possible techniques to be implemented, yet accounting for the constraints on size, complexity and power consumption of the whole system architecture.

In [66,67], two identical meandered flare dipoles (with no ground plane and operating at around 300MHz) have been positioned on the surface of a plastic mannequin, one on the back and the other on the chest, to implement beam switching for coverage improvement with respect to a single antenna. The dipoles are fed by a hybrid coupler. When they are fed out-of-phase, the azimuth-plane (H-plane) pattern exhibits two major lobes at the front and back regions. When they are fed in-phase, the pattern becomes more omnidirectional. In [69], a four-branch pattern diversity scheme has been compared through numerical simulations with a monopole whip antenna. The multi-antenna system comprises four asymmetric thick dipoles integrated on the front/back and left/right ceramic plates of an armor vest. An RF switch controlled by a microcontroller has been used to select the proper dipole. Selection combining diversity has been implemented. In [143], four different geometries of asymmetric dipoles have been integrated into a life vest to experimentally quantify the advantages of a selection diversity scheme in an indoor environment, at UHF band. The grounded meandered dipoles designed in [91] was intended for the use in a two-antenna scheme in which the transmitter can switch between them in order to cover most of the Cospas-Sarsat satellite constellation (Figure 10). Indeed, the two antennas provide complementary radiation patterns so that Cospas-Sarsat requirements (satellite constellation coverage and EIRP profile) are fully satisfied.

In [144], two (grounded) spiral-mode microstrip antennas mounted on the front and rear parts of a military protective vest, respectively, have been used to achieve omnidirectional spatial coverage in the azimuthal plane, over a wide frequency band (225-1000GHz). The two elements of the array are fed in-phase and the diameters of the front-side and rear-side spiral antennas equal 30cm and 18cm, respectively. The thickness is less than 2cm for both antennas. The spiral-mode microstrip antenna radiates a circularly polarized field above 300MHz, and a slanted linear polarization at the lower frequencies, with the slant angle changing with frequency. With respect to other vest antennas, the conformal vest antenna in [144] reduces the radiation hazard and improves antenna efficiency, since it includes a shielding ground plane.

An adaptive cylindrical array of helmet-integrated antennas can be employed to implement an effective pattern diversity technique in the azimuthal plane. In [145,146], the array is made of four wideband, low-profile, grounded and conformal spiral-mode microstrip antennas, which have been mounted on the curved surface of a Kevlar helmet. A fifth spiral-mode microstrip antenna on top of the helmet improves overhead coverage in the vertical plane (in [146], the latter element has been substituted with a low-profile GPS antenna). The wideband helmet antennas have been realized by exploiting spiral-mode microstrip antenna and slow-wave antenna technologies [147,148]. In [147], the wideband travelling wave antenna integrated into a standard Kevlar helmet covers the 1350-2700MHz band, and exhibits a broad pattern in the vertical plane, with nulls in the zenith and ground directions. The antenna occupies a circumferential strip near the top of the helmet and is less than 1.25cm thick. In helmet antennas, the radiating elements are located very close to the human head, so radiation hazard is an extremely important issue. In [147], a conductive cloth lining on the helmet inner surface has been used to provide wearer’s protection to RF hazards. A similar configuration was designed to cover the 600-4000MHz band [148]. It is worth noting that the hard part of the helmet is usually made of strong plastic or Kevlar and the internal part contains protective foam, and all above materials are transparent to EM waves. Moreover, when compared to vest and whip antennas, a helmet antenna is a more rugged antenna, as the helmet is a rigid and stable platform.

A low-profile wideband (300-1000MHz) elliptical monopole realized on a 10.2cmx10.2cm ceramic substrate (anatase titanium dioxide, relative permittivity close to 100, thickness=3mm) was suggested in [149], to be used as a compact radiator for personal radios and short-range radars. The monopole size is around one tenth of the free-space wavelength at 300MHz. The measured gain of the free-standing monopole is only -5dBi, due to the large miniaturization factor. The antenna is suitable for integration in a tactical vest or manpack/backpack. The small radiating element was used to realize an eight-element linear array (inter-element distance of 25cm) for a short-range portable radar. The array length is 175cm, which is approximately equal to the maximum distance between the right and left hands of an adult with arms stretched out.

### 6.B Multi-antenna systems for wideband coverage

Reliable transmission of data, video and voice information, over an extremely wide bandwidth, is of great interest for modern wireless applications. A multi-antenna system can be a technique to implement an efficient wideband system, which meets most of the requirements for wearable antennas.

The authors of [150,151] have designed, prototyped and tested, three different wearable flexible wideband antennas: a loaded dipole covering the 100-250MHz band, where lumped components are used to enlarge the impedance bandwidth; a bow-tie antenna and a circularly-polarized spiral antenna, both able to cover the upper band from 250MHz up to 500MHz. To facilitate measurements when the antenna is in proximity of the human body, the spiral was adhered to a thin sheet of acrylic which was deformed to make it approximately conformable to the torso. Measurements have been performed in a cylindrical near-field test facility. It was found that the distance of the antenna from the body is critical even at the lower frequencies. The spiral antenna positioned on the torso covers only one hemisphere. Another antenna on the back should be used to obtain on omnidirectional pattern in the azimuthal plane. Only one dipole along the leg suffices to meet azimuth omnidirectional coverage requirements at the lower band. A long dipole was designed to be installed from the top of the shoulder, down the back and along the leg to the ankle (“full-body” antenna). In [152], a large variety of materials and manufacturing techniques (conducting nylon sheets, copper coated fabric, weaving conducting thread, conducting ribbon, insulated wire, conducting paint, phosphor bronze mesh, screen printing conducting inks and spray conducting paints, liquid crystal polymer) have been compared by measuring antenna input impedance and gain, when the antennas in [150,151] were worn by a human. Some of the above tested materials cannot be soldered on. In that case, crimp-type connectors or conductive epoxy have been used. The authors concluded that the conducting nylon and the copper-coated fabric provided the best results, in terms of both manufacturing and RF performance.

The COMbat Wear INtegration (COMWIN) antenna system has been developed for the man–portable implementation of the ultra-wideband Joint Tactical Radio System (JTRS), by researchers at the SPAWAR Systems Center, San Diego, CA, in association with the Naval Postgraduate School in Monterey, CA [153-158]. The COMWIN system consists of three antennas to guarantee a 2MHz-2000MHz frequency coverage: 1) a whole-body antenna in the form of flak jacket, pants and shoes, which is able to receive at any frequency from 2 to 30 MHz (a feed is located on the back of the flak jacket, with two arms that go down the sides of the soldier; the pants have metal stripes down the sides and the shoes have metal insoles to couple the signal to the ground); 2) a vest antenna covering the band from 30MHz to 500MHz; 3) a helmet-mounted antenna operating in the 500-2000MHz band. Each antenna is hidden by the soldier's uniform, such that the radio operator is indistinguishable from any other soldier. The wideband helmet antenna in [155,156] is one of three antennas based on the antenna COMWIN concept. The helmet antenna consists of two radiating surfaces separated by a gap. The top and bottom radiating surfaces are of (approximately) equal surface area and are electrically connected at the front of the helmet by a conducting strip. The inner conductor of the feeding coaxial cable is soldered to the upper half of the antenna while the outer conductor (shield) is soldered to the lower half. The two radiating surfaces are made of thin polyester fabric interwoven with nickel/copper fibers. The antenna is then attached as a liner to the helmet's camouflage cover. The antenna is vertically polarized with an almost omnidirectonal pattern in the azimuthal plane. It is conformal to the shape of a Kevlar ballistic helmet. A prototype of the helmet antenna with a gap of 0.5cm thickness covers a 500-2000MHz instantaneous bandwidth. Another version of the helmet antenna, with the gap thickness that changes from a minimum of 0.5cm to a maximum of 8.5cm (at the top of the helmet), achieves a larger bandwidth (300-3000MHz). The COMWIN vest antenna [154,157,158] can be considered as a horizontal slot realized into a conducting vertical cylinder of finite length, all around the wearer's body. It was made out of Flectron, which is a mixture of copper interwoven with polyester to form a high conductivity fabric. The vest width is 50cm, the depth is 20cm and the height is around 67cm. The vest antenna was integrated into a Kevlar flak jacket to get no visual signature. For both helmet and vest antennas, it has been verified that the number of lobes and the depth of the nulls, in the azimuth-plane radiation pattern, increase as the frequency increases.

In [159], two arrays have been used to cover the complete frequency band from 50MHz to 2GHz. The first array includes four bow-tie antennas and operates in the 50-650MHz band. Each element is made of antipodal pairs of 22cm long tapered strips of Nickel/Silver metalized ripstop nylon fabric. The second array consists of six printed tapered slots. It is used to cover the 650-2000MHz frequency band. In each array, a uniform excitation was applied. Both arrays are connected to the radio/receiver by means of a diplexer, without the need for switching the arrays. The antennas surround the wearer's body in order to mitigate body shadowing effects and thereby achieve an omnidirectional pattern in the azimuth plane. The array configuration can also be used to implement a beam switching antenna. The implementation of effective phased arrays at the VHF and UHF bands is severely limited by small values of the electrical distance between elements that can be actually realized on a human body.

## 7. Discussion and Future Trends

The design of VHF/UHF antennas that are sufficiently lightweight, conformable and flexible to be worn by a user is a challenging issue, mainly in the lower frequency range. Although the relatively large amount of real estate available on the human body and the high dielectric permittivity of the human tissue can help to realize electrically large antennas, the human body losses severely reduce antenna efficiency. At VHF band, typical realized gain values for wearable antennas worn by a user are less than -10dBi, and most of the antennas are simple dipoles or loops. Indeed, effective reflectors and ground planes (being shielding surfaces that are large with respect to the free-space wavelength) are not applicable to antennas that may not obstruct body movements. When moving to the UHF lower band, antenna gain values larger than -5dBi can be obtained, with antennas whose size is of the order of a few tens of cm. An effective technique to increase the antenna efficiency consists of inserting a spacer between the antenna and the body surface. However, a large distance between antenna and body is in apparent contrast with the low-profile requirement for planar and conformable wearable antennas. Yet, it can be an acceptable solution whenever the antenna is integrated into specific garments, such as life jackets, armor vests, protective garments, etc., by exploiting the thickness and the electromagnetic characteristics of the materials they are made of. Finally, at the UHF upper band, antenna gains between 2 and 5dBi become typical values for body-worn antennas, as multi-layer grounded antennas can be implemented. Indeed, quarter-wavelength or half-wavelength sized antennas can be accommodated on different on-body positions, as their overall physical size can be lower than 15cmx15cm (see the numerous antenna layouts for UHF RFID tags described in Section 5.B).

When high performance is required in terms of antenna gain and radiation patterns, multi-antenna systems can be used, in order to implement switched beam capabilities, diversity schemes or MIMO techniques. However, the advantages of a multi-antenna system must compensate for the complexity of the wired network required to connect all the antennas and combining/switching devices.

The utilization of conductive fibers and fabrics for the integration of antennas into clothing and garments is particularly useful for wearable antennas at the VHF/UHF bands, as fully textile antennas help to realize antennas that can be physically large, yet flexible, comfortable to the user and unnoticeably embedded. Nonetheless, novel conductive fibers/textiles and suitable construction techniques should be made available, to allow the implementation of robust textile antennas with more complex topologies, which can help designers to achieve higher performance when the antenna is body worn. It is expected that, in the near future, textile antennas will represent most of the VHF/UHF wearable antennas. In this context, techniques for the electromagnetic characterization of textile materials and fibers are of prime interest. In addition, the long-term reliability of smart textiles, taking into account maintenance procedures such as washing and dry-cleaning, should be further improved.

Well-known technologies such automatic tunable circuits and antenna reconfigurability (which are already widely applied in portable devices, such as mobile phones and digital radio/television receivers) could be implemented in a wearable antenna, to counter antenna detuning (reconfigurable wearable antennas) [160]. VHF/UHF wearable antenna reconfigurability is also of interest for the implementation of wideband off-body communication systems, such as software-defined-radio systems, opportunistic communications systems, cognitive radio systems. An electronically reconfigurable system, along with multiple antennas in the field-of-view over much of the body, is a good candidate to adapt antenna performance to the environment variations induced by the wearer's movements and random fluctuations in antenna-to-body distance.

Finally, conventional techniques for the characterization of antennas should be modified to account for the dependence of antenna performance parameters on a number of random phenomena: wearer's body posture, wearer's natural movements, distance between the antenna and the body surface, environmental conditions and mechanical deformations (mainly for textile antennas). Currently, those effects are usually taken into account by over-specification of the design requirements, which may result in uneconomical solutions. Further studies should be devoted to the development of a stochastic framework for the design and characterization of wearable antennas [161], which would allow the system designer to easily, yet accurately, estimate the performance of a wireless system for a given model of the user scenario. This new framework must be able to deal with variability in both the antenna performance and propagation environment.

Textile antennas also offer great potential for new emerging applications, such as RF energy harvesting, wireless power transfer [105-107] and indoor localization. At VHF/UHF frequencies, the low path loss, combined with the large area a garment provides novel opportunities for wearable antennas to increase the efficiency and accuracy of such systems. Moreover, textile antennas may also serve as platforms to implement distributed exposimeters [162] that accurately monitor RF field levels the human body is exposed to.

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# FIGURE CAPTIONS

Figure 1 - Hypothetical physical size of an efficient radiator versus frequency (30MHz<f<3GHz): antenna size=$\lambda$, $\lambda/2$ or $\lambda/4$; below $0.1\lambda$ for electrically small antennas ($\lambda$ is the free-space wavelength). As a reference, the average dimensions of body sections [9] are given in the same figure for an adult (1.75m tall and 85Kg weight): 175cm: height, hand-to-hand distance with arms stretched-out; 75cm: torso height, legs length; 40cm: torso/back width, upper arm length.

Figure 2a Relative permittivity and effective conductivity for muscle tissue, in the VHF-UHF band [11].

Figure 2b - Wavelength and penetration depth for muscle tissue, in the VHF-UHF band (as a reference, a curve for free-space wavelength is also shown; note that the left and right scales differ by one-order magnitude).

Figure 3a - Electrotextile patch antenna.

Figure 3b - Patch antenna etched in copper on a thin ultra-flexible polyimide substrate.

Figure 3c - Screen-printed textile patch antenna.

Figure 3d - Copper-foil patch antenna on textile substrate.

Figure 4 – Textile antenna implemented in substrate integrated waveguide technology [53].

Figure 5a - A wide four-finger half-wavelength dipole for FM receivers [57].

Figure 5b - A normal mode helix designed to be located along the human arms, with the helix wrapped around one user's arm, for FM receivers [57].

Figure 5c - A VHF multiresonant antenna made of five embroidered folded dipoles connected in parallel, designed for FM reception [58].

Figure 5d - A flexible third-order Minkowski fractal antenna that has been designed to operate with Land Mobile Radio systems at 136MHz [59].

Figure 6a - A grounded antenna made of two slot-coupled patches, operating at the 380-390MHz band, for over-the-shoulder positioning [64,65].

Figure 6b – A conformal asymmetric meandered flare dipole for communications at 300MHz [66,67].

Figure 6c – An asymmetric dipole operating in the 225-450MHz band and realized on the ceramic tile of armored vests (ceramic bulletproof plates of the Improved Outer Tactical Vest body armor) [69].

Figure 6d – A shoulder-mountable low-profile PIFA for narrowband professional radios at 350MHz (the coaxial feed is not shown) [71,72].

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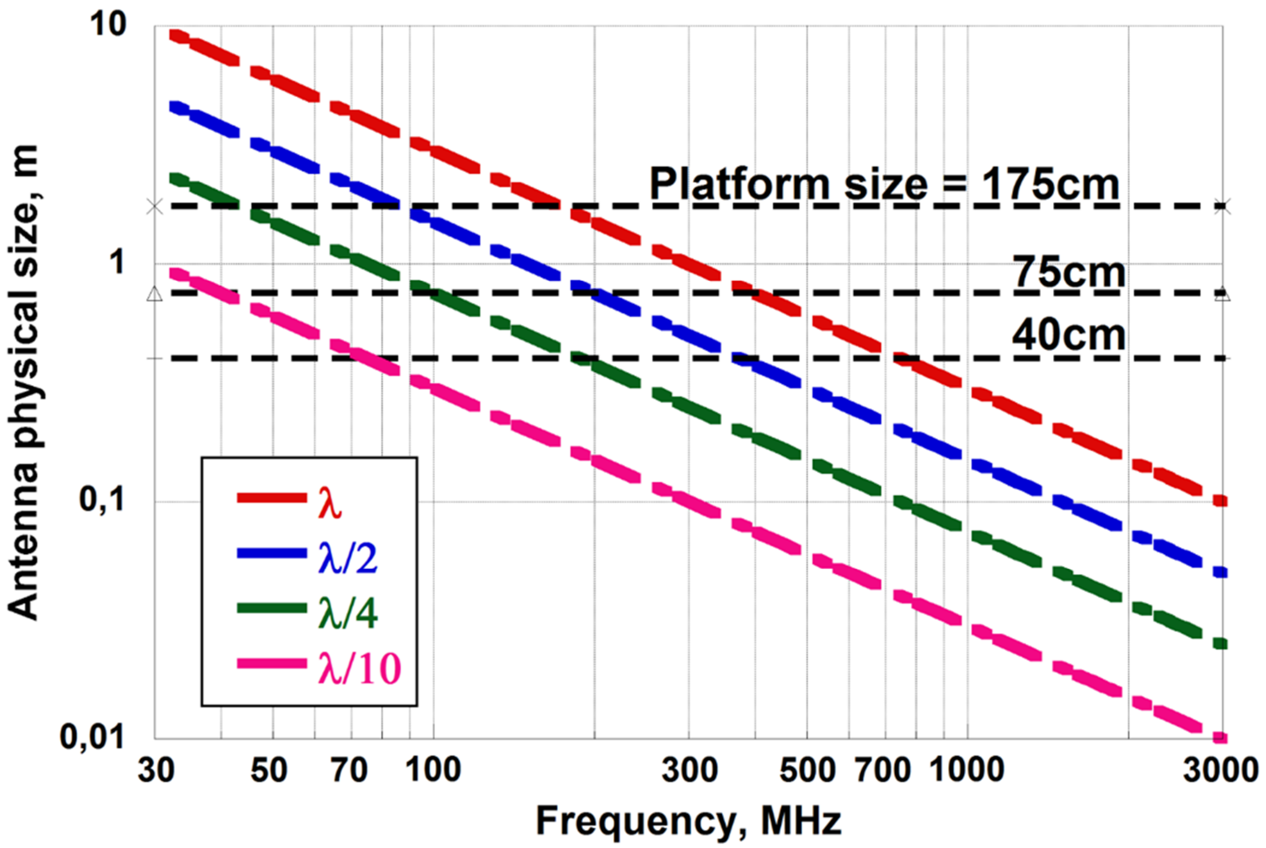

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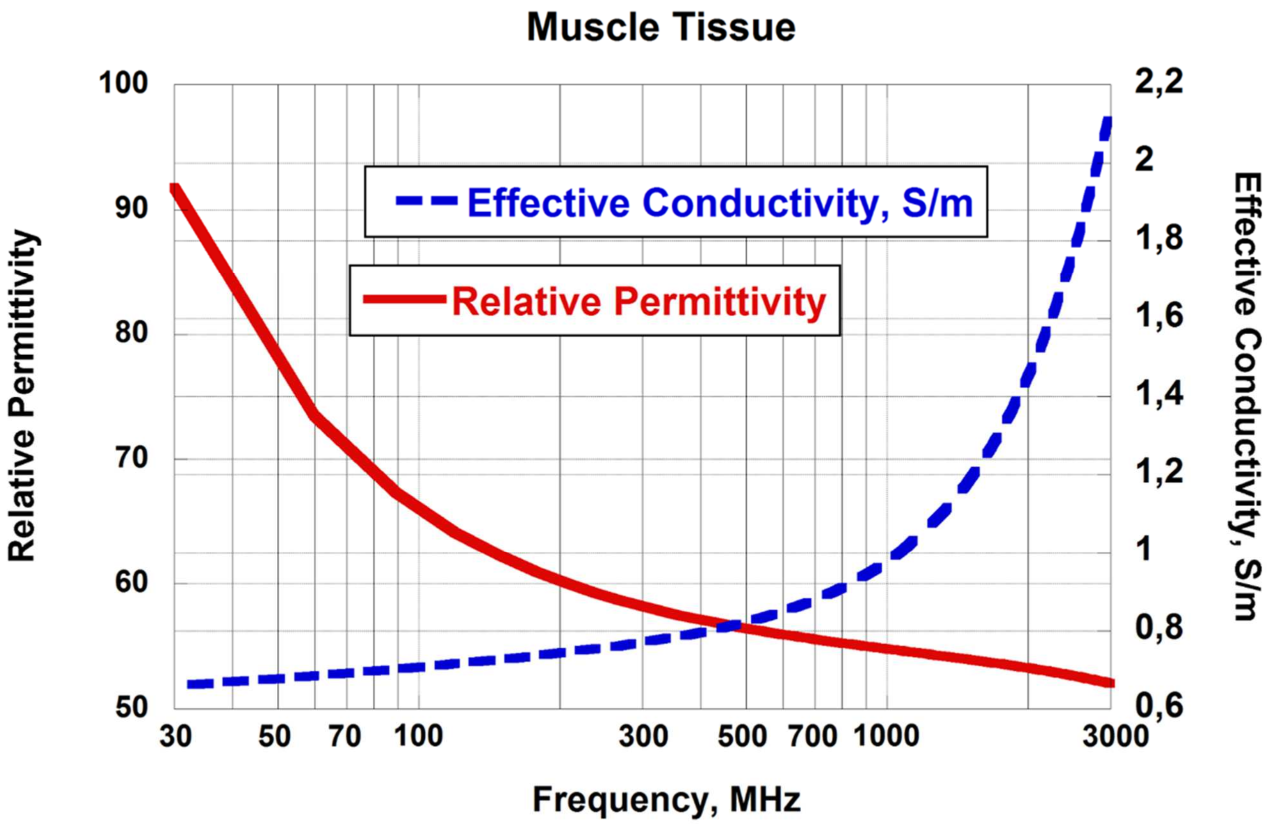

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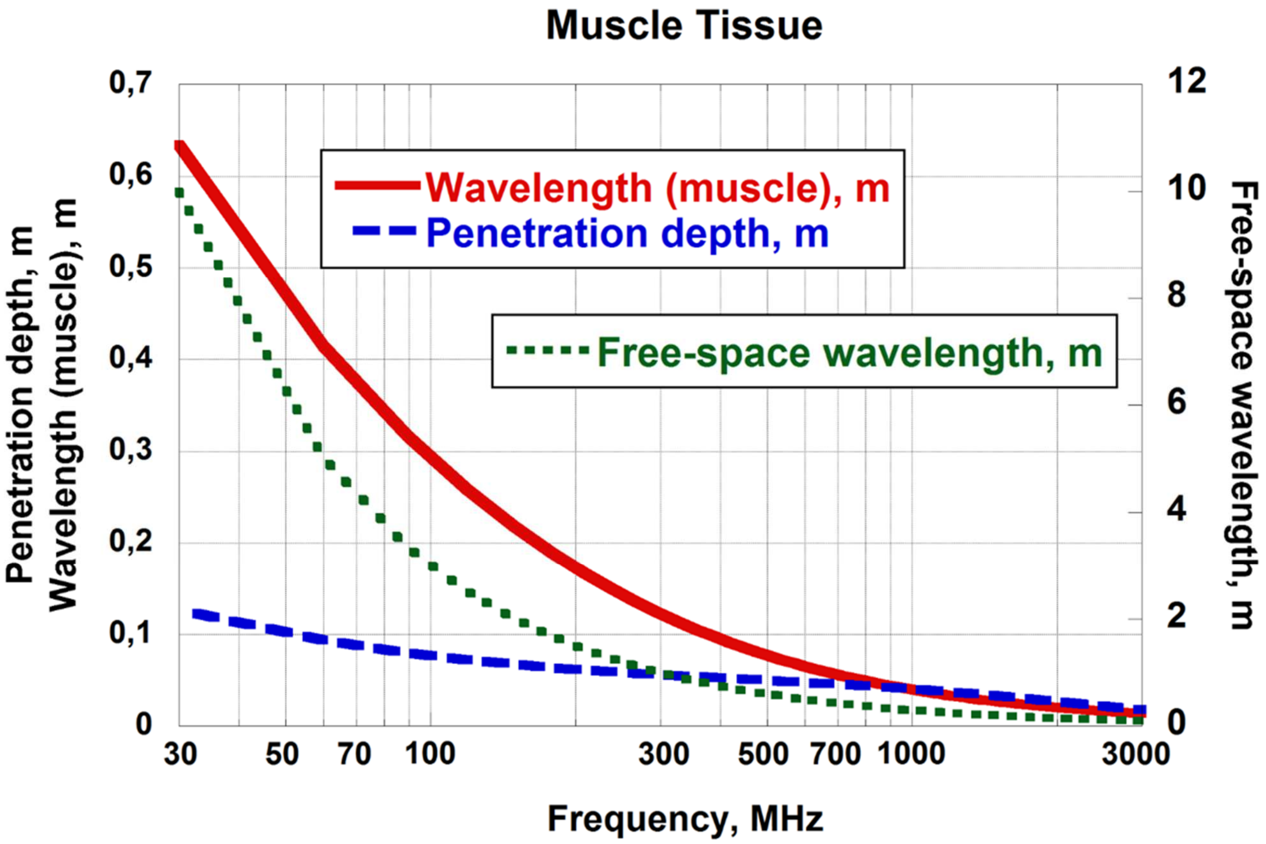

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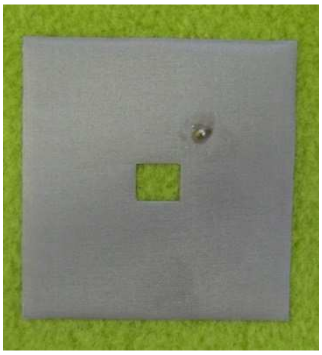

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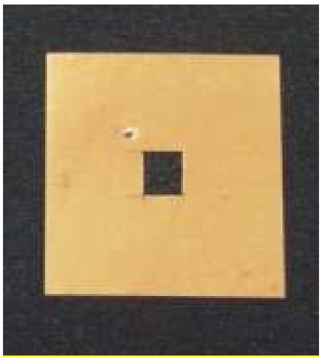

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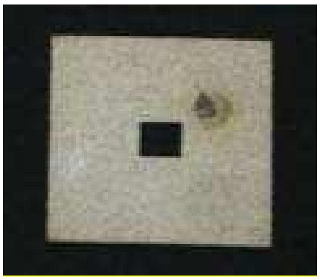

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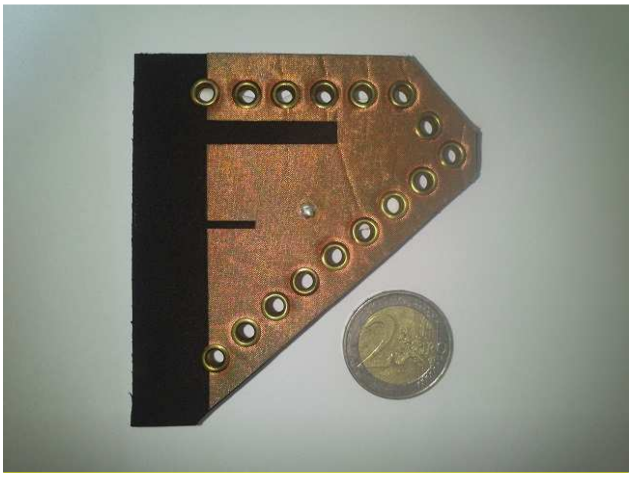

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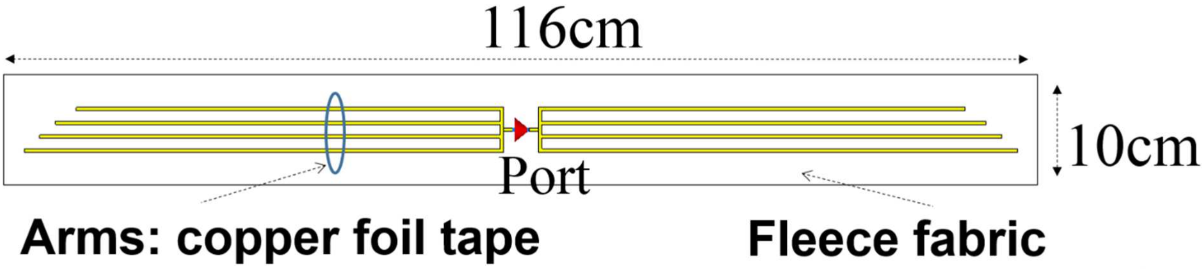

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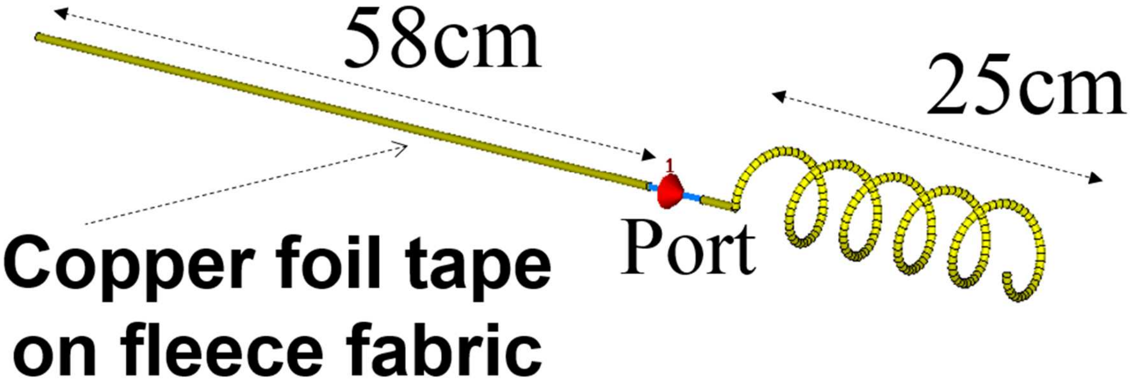

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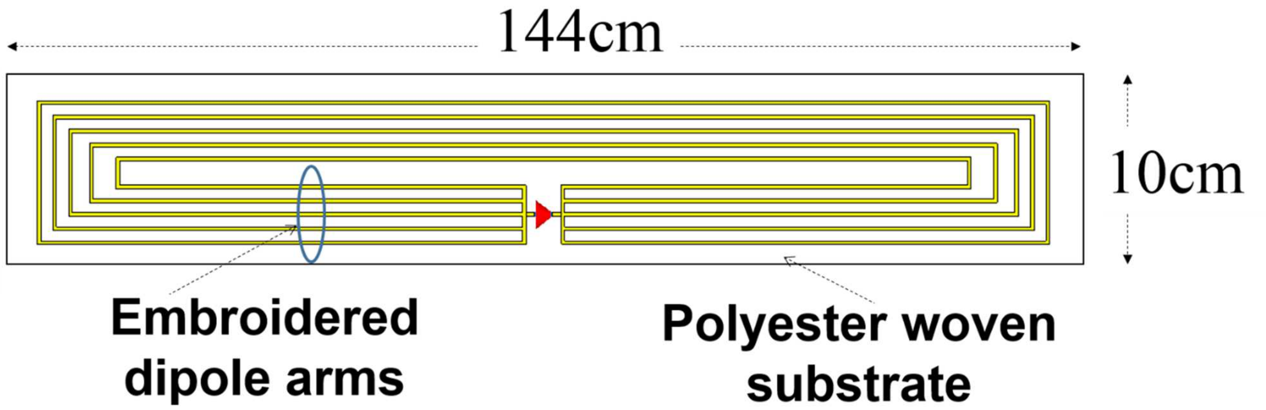

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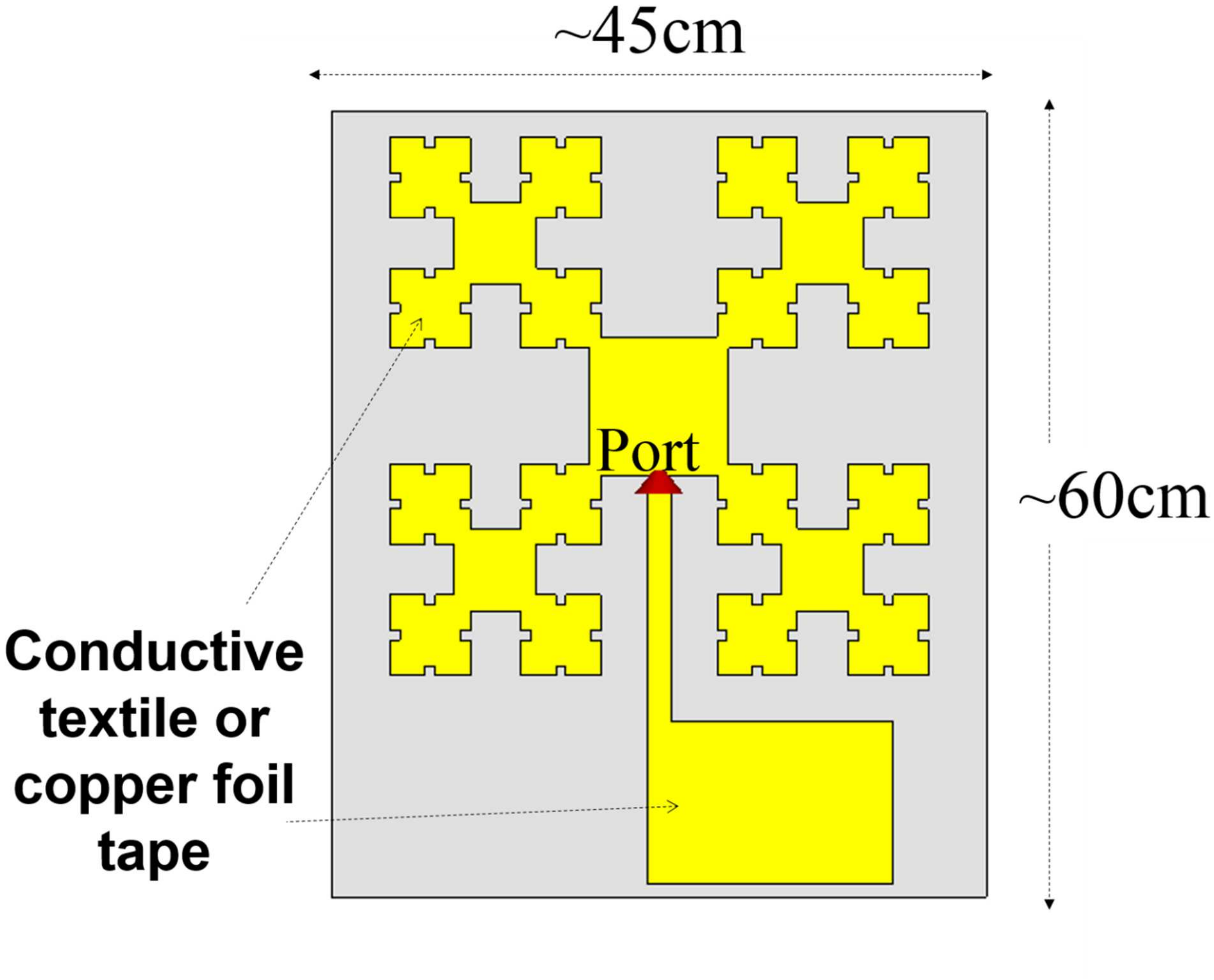

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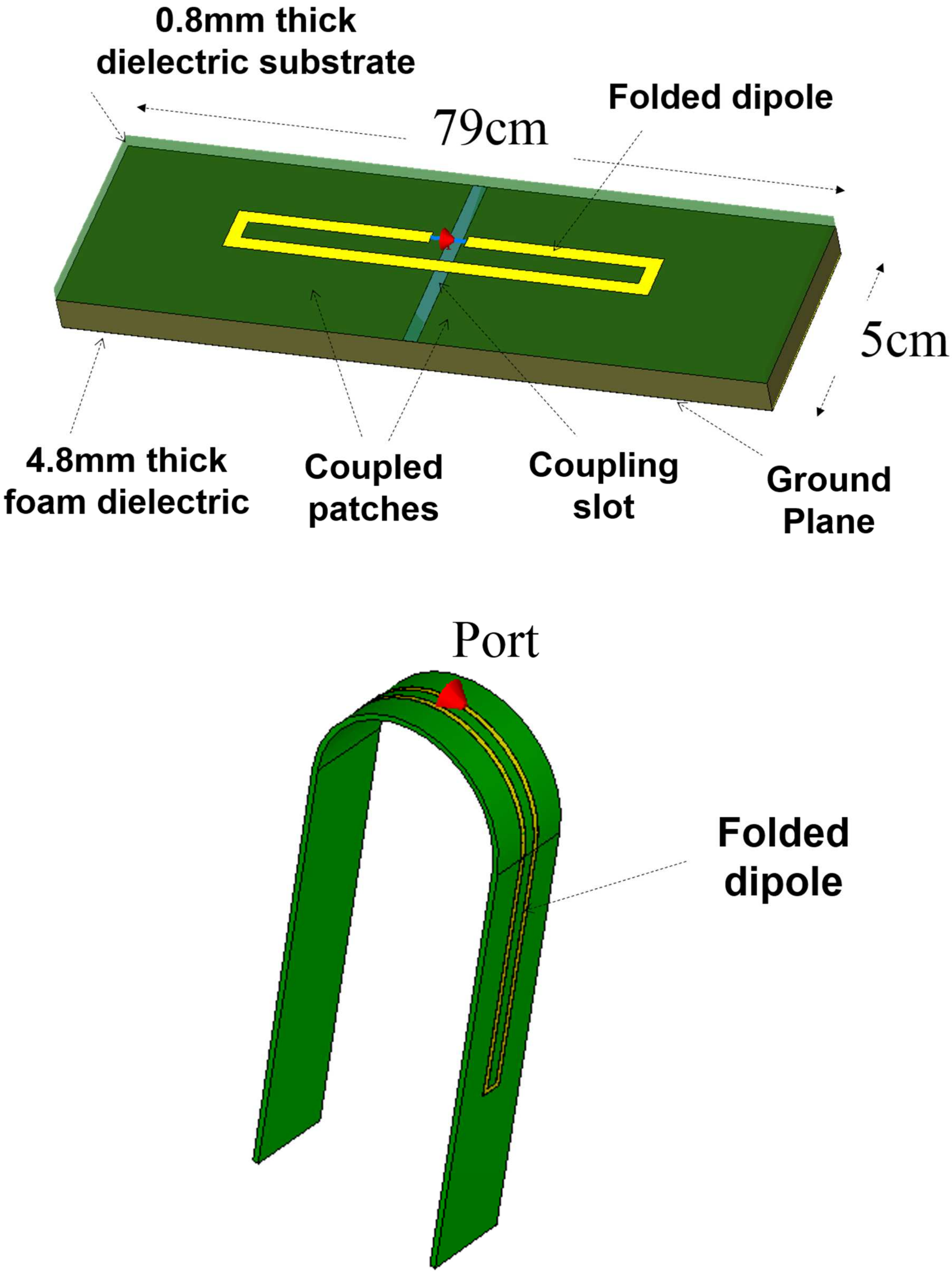

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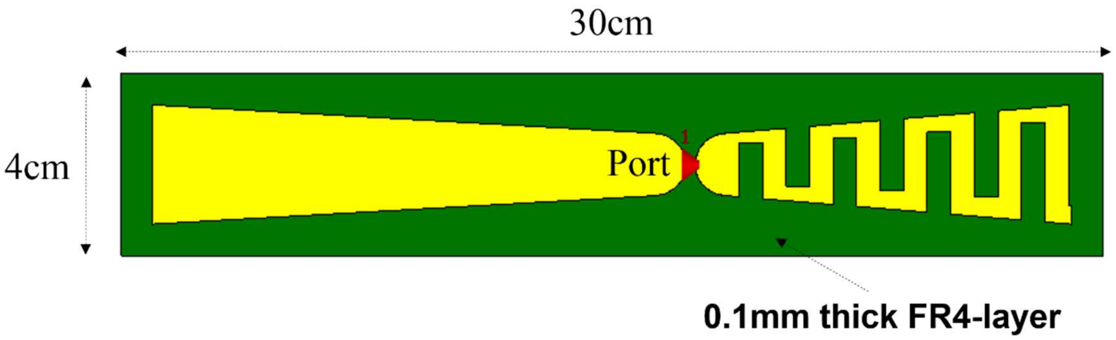

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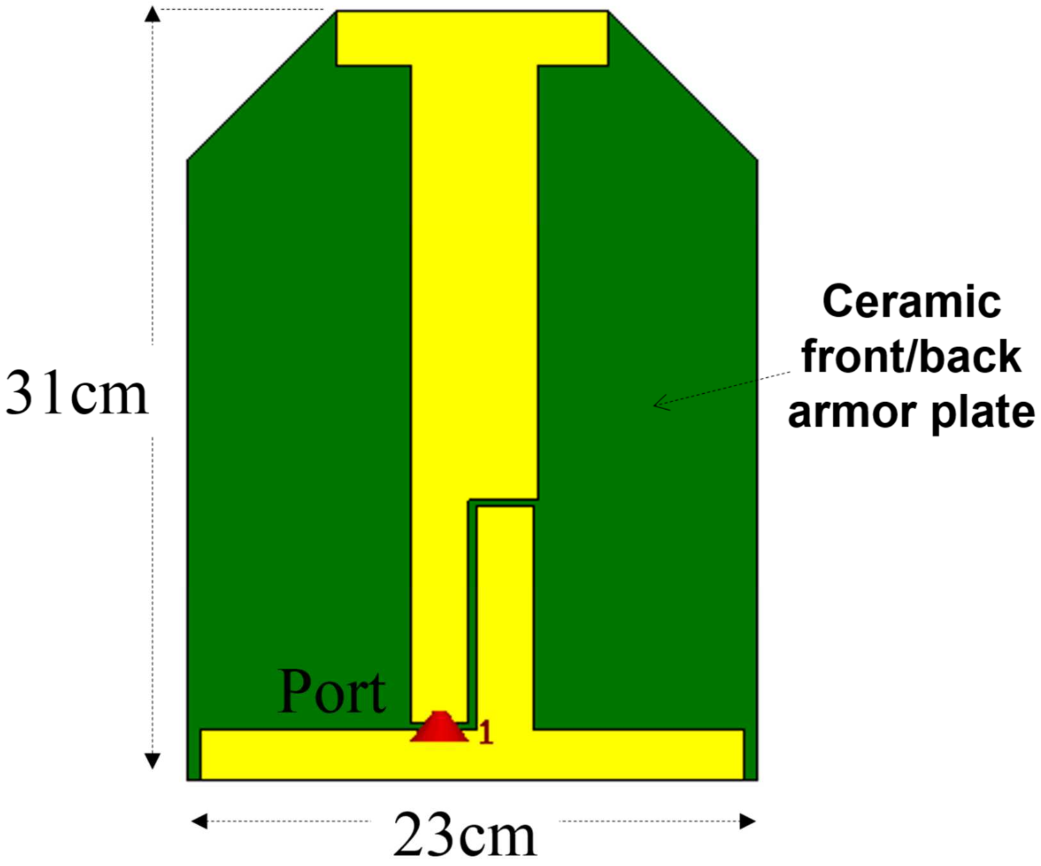

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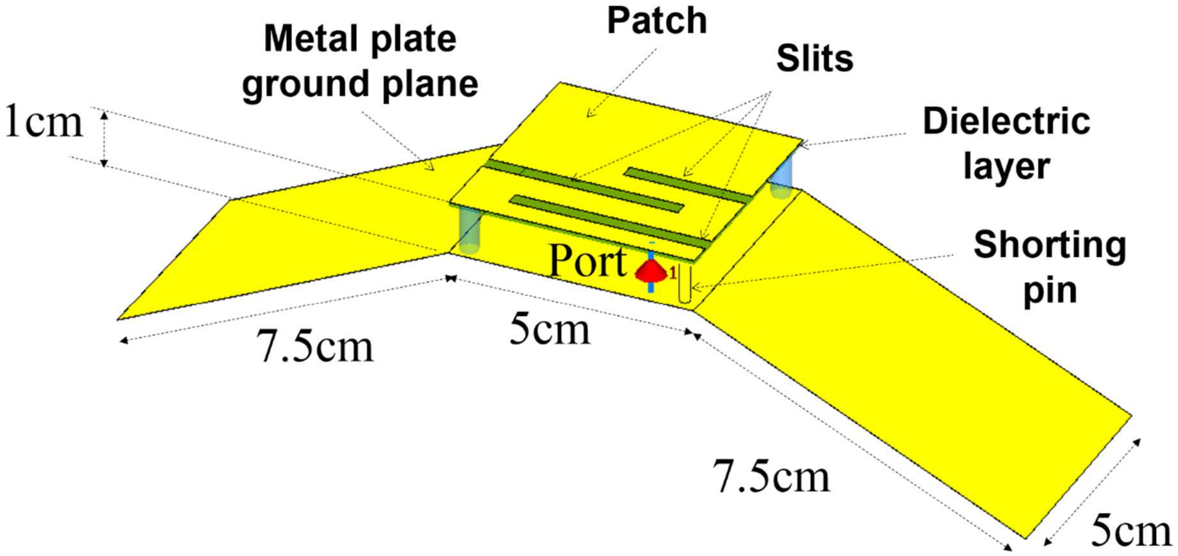

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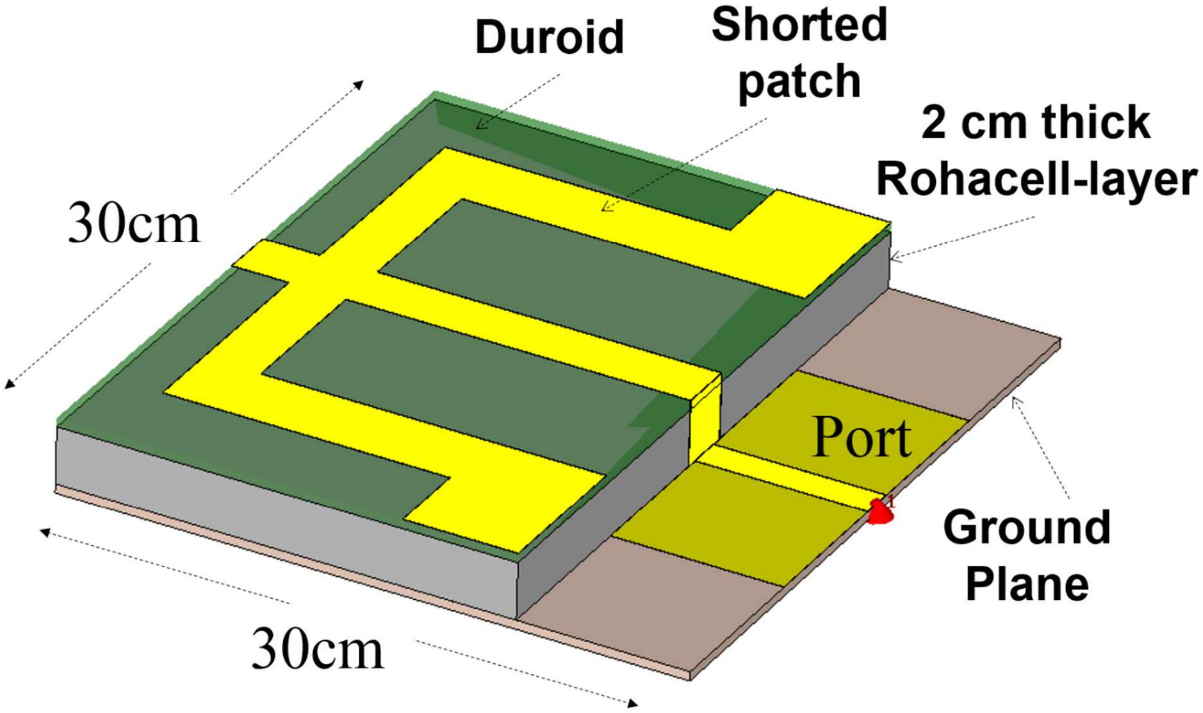

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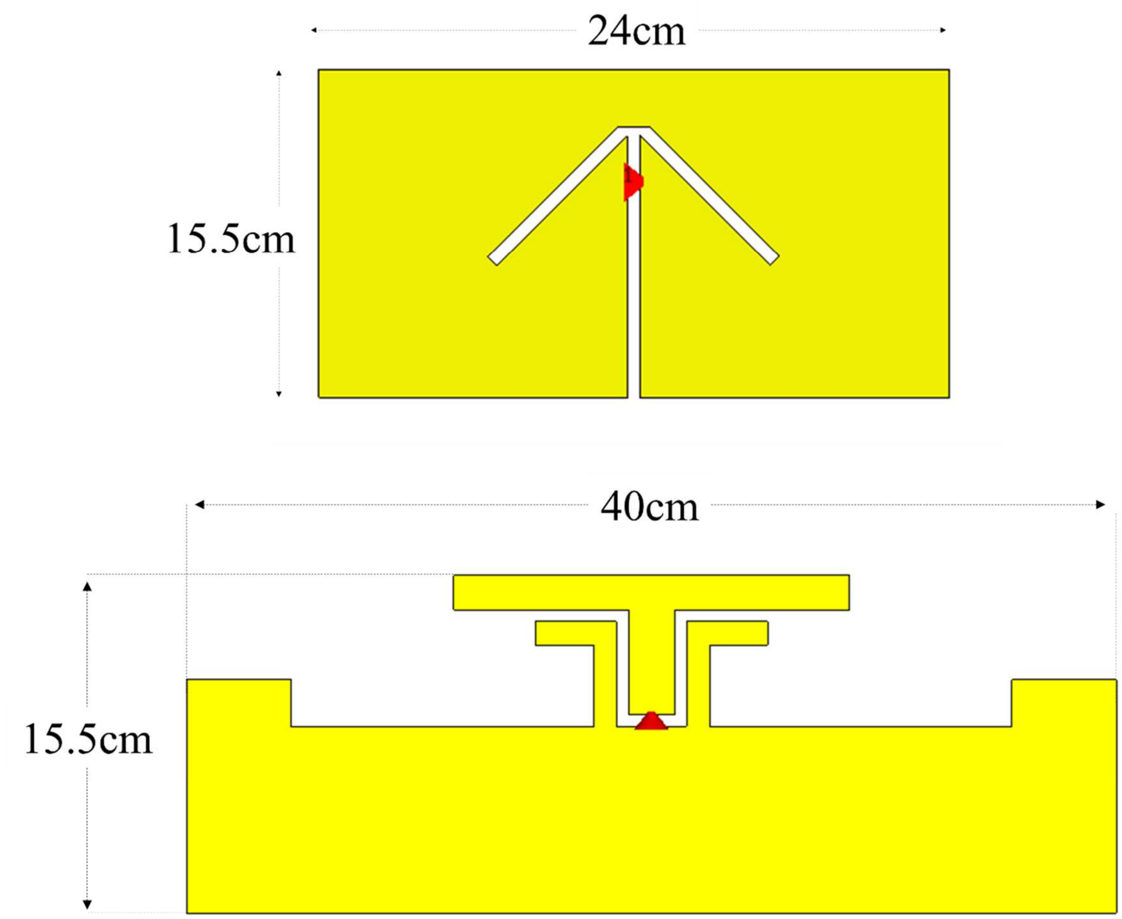

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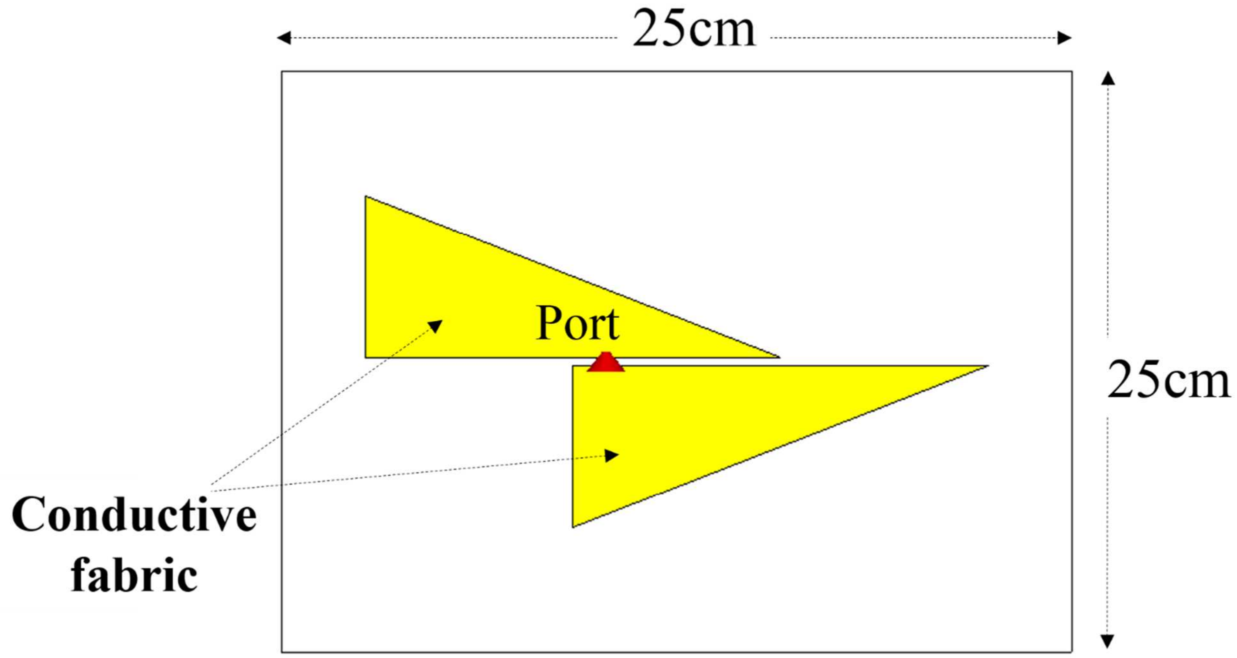

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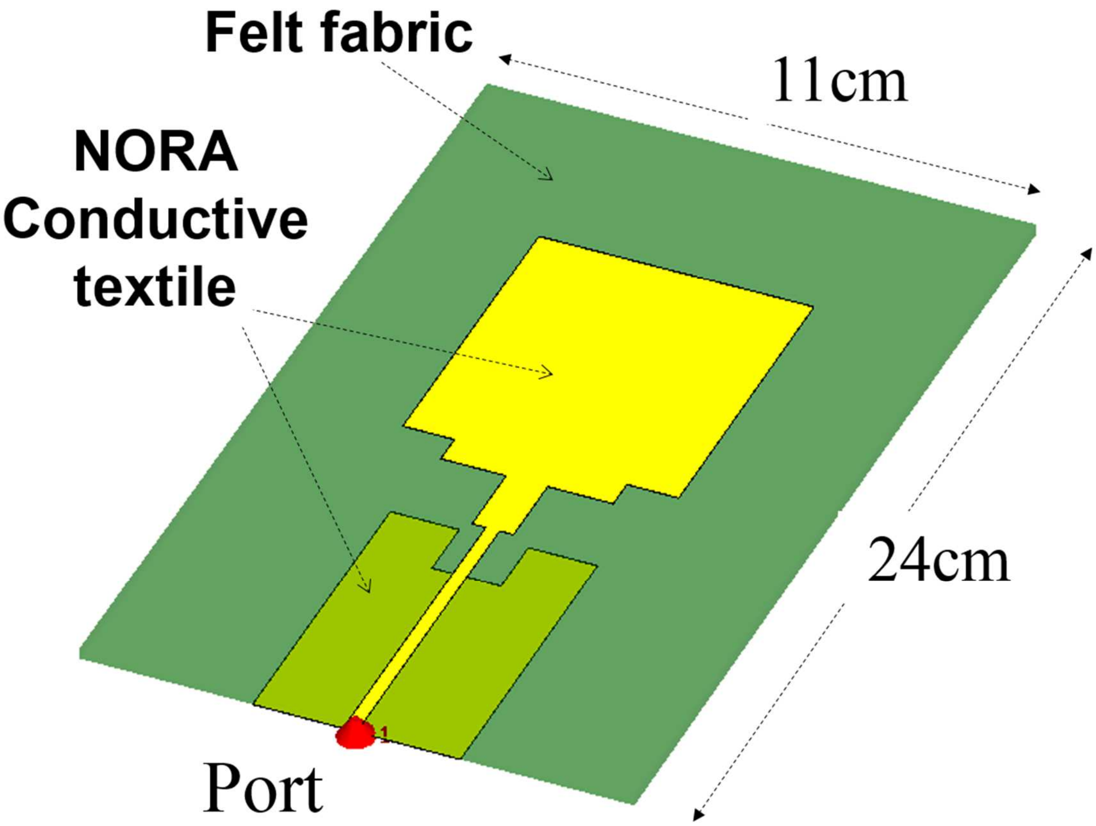

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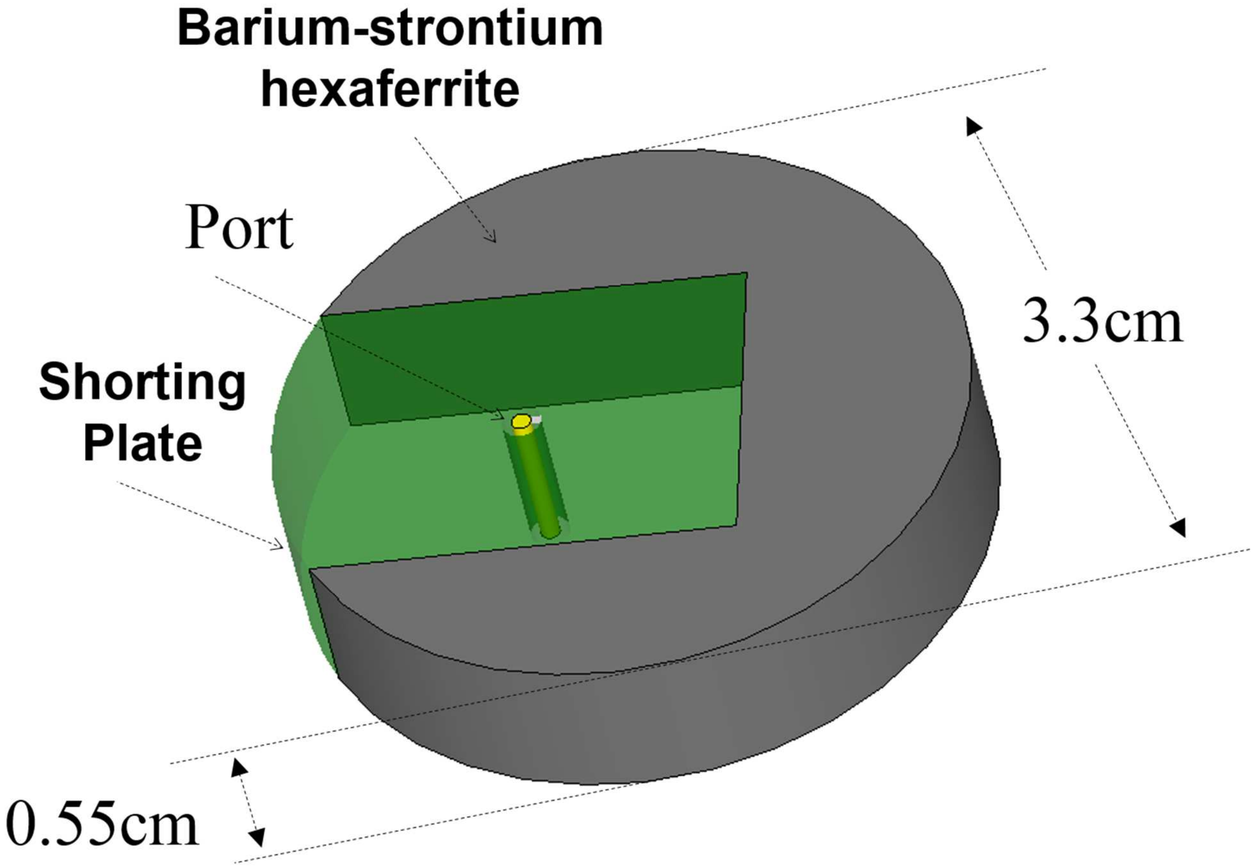

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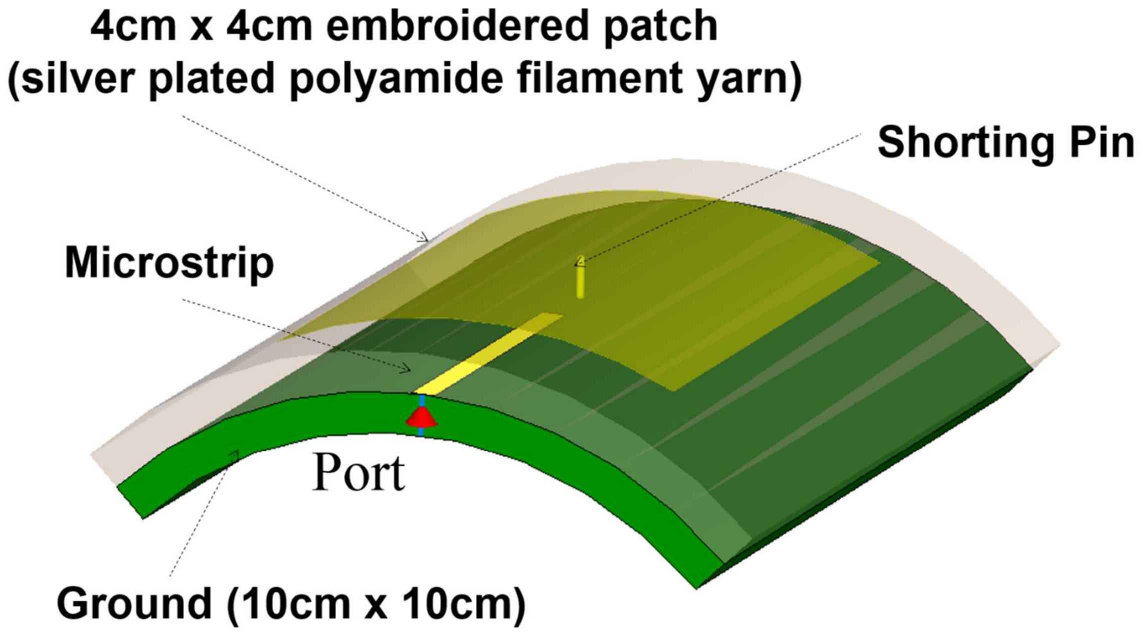

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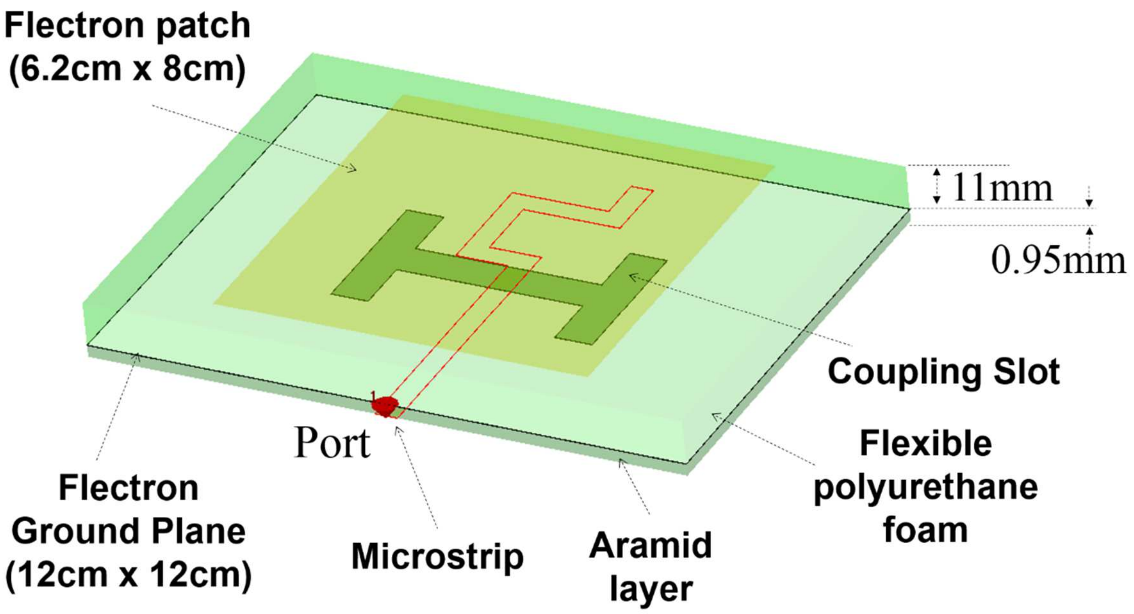

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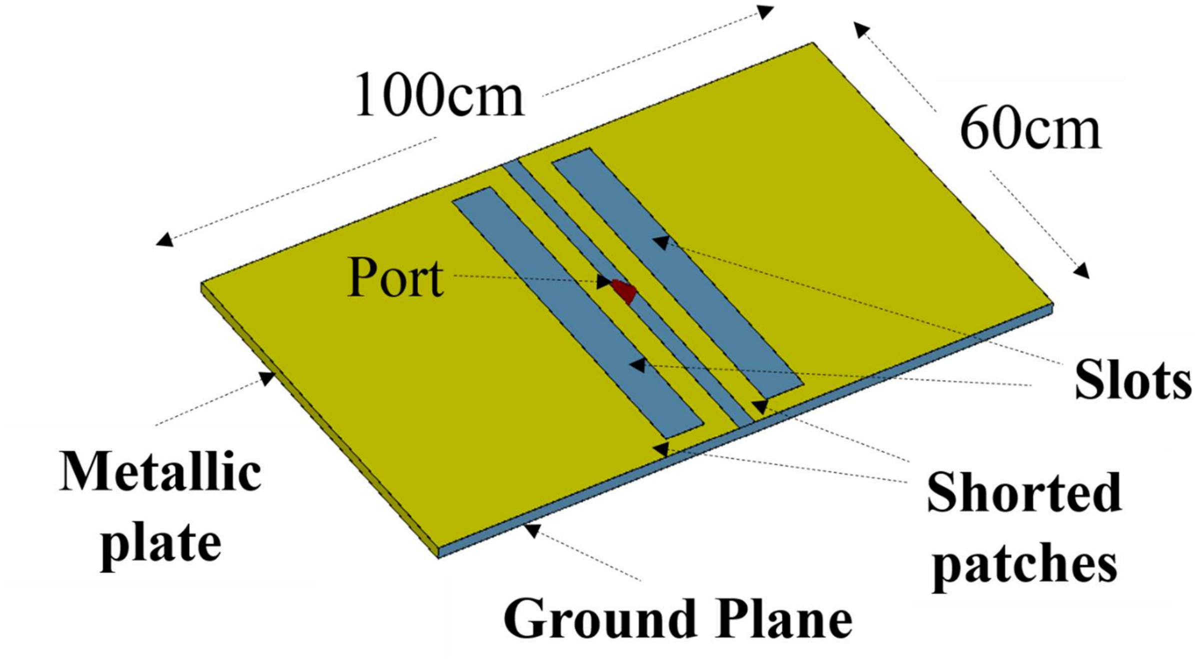

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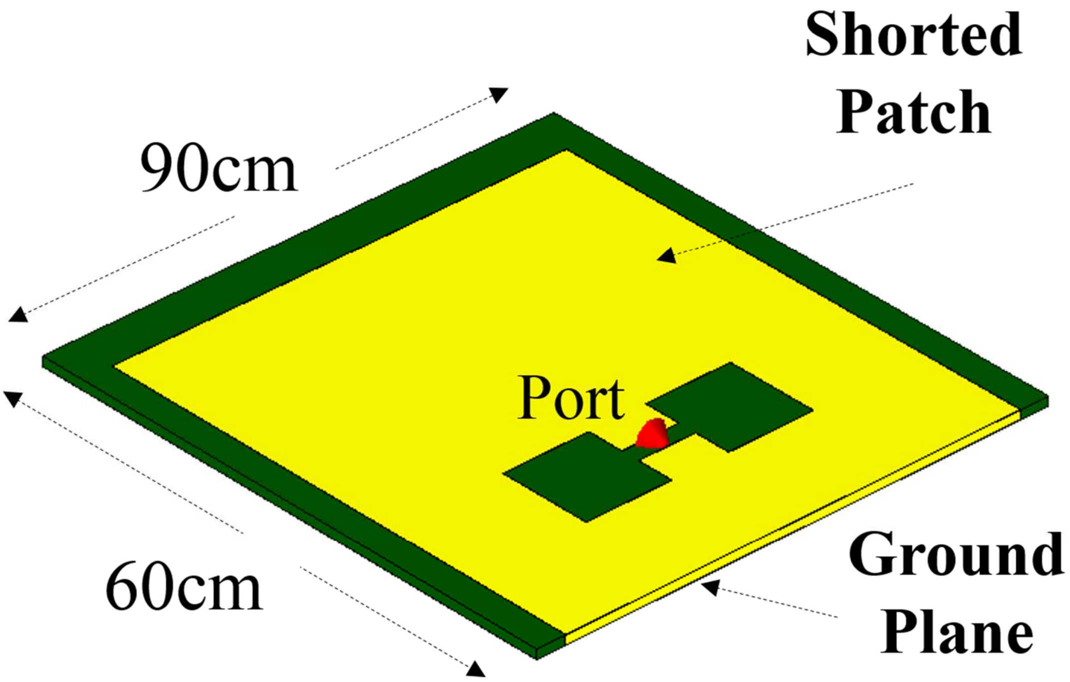

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Paolo Nepa received the Laurea (Doctor) degree in electronics engineering (summa cum laude) from the University of Pisa, Italy, in 1990. Since 1990, he has been with the Department of Information Engineering, University of Pisa, where he is currently an Associate Professor. In 1998, he was at the Electro Science Laboratory (ESL), The Ohio State University (OSU), Columbus, OH, as a Visiting Scholar supported by a grant of the Italian National Research Council. At the ESL, he was involved in research on efficient hybrid techniques for the analysis of large antenna arrays. His research interests include the extension of high-frequency techniques to electromagnetic scattering from material structures and its application to the development of radio propagation models for indoor and outdoor scenarios of wireless communication systems. He is also involved in the design of wideband and multiband antennas, mainly for base stations and mobile terminals of communication systems, as well as in the design of antennas optimized for near-field coupling and focusing. More recently he is working on channel characterization, wearable antenna design and diversity scheme implementation, for body-centric communication systems. In the context of RFID systems, he is working on techniques and algorithms for UHF-tag localization and RFID-based smart shelves. He received the Young Scientist Award from the International Union of Radio Science, Commission B, in 1998.

Hendrik Rogier received the M.Sc. and Ph.D. degrees in Electrical Engineering from Ghent University, Gent, Belgium, in 1994 and in 1999, respectively. He is a currently a Full Professor with the Department of Information Technology of Ghent University, Belgium, Guest Professor at iMinds, Ghent, Belgium, and Visiting Professor at the University of Buckingham, UK. From October 2003 to April 2004, he was a Visiting Scientist at the Mobile Communications Group of Vienna University of Technology. He authored and coauthored more than 110 papers in international journals and more than 125 contributions in conference proceedings. He is serving as a member of the Editorial Board of IET Science, Measurement Technology and of Wireless Power Transfer. He acts as the URSI Commission B representative for Belgium. Within the IEEE Microwave Theory and Techniques Society, he is a member of Technical Committee 24 on RFID technology and within the European Microwave Association, he is a member of the Governing Board of Topical Group MAGEO on Microwaves in Agriculture, Environment and Earth Observation. His current research interests are antenna systems, radiowave propagation, body-centric communication, numerical electromagnetics, electromagnetic compatibility and power/signal integrity. Dr. Rogier was twice awarded the URSI Young Scientist Award, at the 2001 URSI Symposium on Electromagnetic Theory and at the 2002 URSI General Assembly. In addition, he received the 2014 Premium Award for Best Paper in IET Electronics Letters, the Best Poster Paper Award at the 2012 IEEE Electrical Design of Advanced Packaging and Systems Symposium (EDAPS), the Best Paper Award at the 2013 IEEE Workshop on Signal and Power Integrity (SPI) and the Joseph Morrissey Memorial Award for the First best scientific paper at BioEM 2013.