Chapter: Latest developments in the field of textile antennas

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1. Introduction to textile antennas

Textile antennas are a special class of antennas that are partially or entirely made out of textile materials, in contrast to conventional antennas, which consist of rigid materials. The textiles composing a textile antenna are divided into electrically conductive fabrics, denoted electrotextiles and applied for the radiating and grounding parts, and dielectric materials for the insulating parts of the antenna.

As can be intuitively understood, the reason behind the use of textile materials in antennas lies in the application for which they are intended, being *smart textile systems* and *body-centric communication*.

Smart textile systems represent a new concept of garments that, in addition to traditional functions such as protecting the body against the environment, also offer additional functionality such as *sensing*, *actuating* and *communication*, realized by wearable devices that are integrated into the “smart” garment. *Sensing functions* are realized by sensors integrated into the textile garment’s material and are intended to detect the state of the wearer (i.e. body temperature, heart rate, position) and/or the state of the surrounding environment (i.e. external temperature and humidity). *Actuating functions* are enabled by garment-integrated actuators that provide signals and/or alarms in order to inform, command or warn the wearer about certain events regarding his/her state or the state of the surrounding environment.

Finally, *communication* is realized in a wireless way by means of an integrated *wearable textile antenna* in combination with a wearable transceiver. Such a kind of wireless communication takes place between the human body and the surrounding environment and is also referred to as *body-centric communication.* In parallel with textile antennas, this has become a very popular field of research over the last decade [1], with crucial importance for plenty of applications, ranging from monitoring of vital signs of patients to coordination and monitoring of rescue workers [2], but also in the entertainment sector [3] and in sports [4].

Suitable topologies for the realization of wearable textile antennas exhibit a low profile and compact dimensions. Those features are particularly convenient for on-body placement and seamless integration into garments. For this reason, the majority of existing textile antennas are *microstrip* or *patch antennas.*

Microstrip antennas, often referred to as *patch antennas,* are very well-known and have received remarkable attention during the last four decades, even though the first idea dates back to the 1950s [5]. The success of microstrip and patch antennas is mainly due to their low profile and conformability to curved surfaces, which made them initially very suitable for integration on surfaces of aircraft, missiles, satellites, ships, and so on. A patch antenna consists of a very thin conductive microstrip, with thickness $t_p \ll \lambda_0$, placed at a certain distance *h* above ground plane (typically $0.003\ \lambda_0 < h < 0.05\ \lambda_0$), as shown in the scheme of Figure 1. The space between patch and ground plane is occupied by a layer of dielectric material, indicated as *antenna substrate*, with a certain permittivity ε_r, loss tangent *tanδ* and thickness *h*. A large variety of different patch topologies have been already proposed and applied by designers throughout the world.

The microstrip patch represented the natural choice when the first wearable antenna (although not made of textile material yet) was envisaged in 1999 by Salonen *at al.* in [6]: a planar inverted-F antenna for GSM application, with a copper patch printed on a circuit board, suitable for garments' integration. Next, the first wearable antenna made out of textile materials was conceived in the Philips laboratories by Massey *et al.* in [7]. Starting from these first prototypes, during the last 15 years, literally dozens of textile wearable antennas where proposed and studied by researchers throughout the world, such as [8, 9, 10, 11]

Figure 1: Scheme of a patch antenna structure.

2. Textile antenna fundamentals

In this section, a brief overview is given of the fundamental textile antenna parameters, followed by the typical guidelines for the design and analysis of textile antennas (as well as conventional ones). For more in-depth information about this topic, we refer to literature textbooks, such as [12].

2.1. Textile antennas performance parameters

Input impedance, Reflection Coefficient and Return Loss

The input impedance of an antenna is defined as the ratio between the voltage and the current at its terminals, when the antenna is in transmit mode. The equivalent circuit representation is displayed in Figure 2.

Figure 2: Equivalent circuit of an antenna in TX mode

The input impedance Z_{in} consists of a real and an imaginary part, called *input resistance* R_{in} and *input reactance* X_{in}, respectively. The input resistance is composed of two parts as well, one due to ohmic losses in the dielectric and conductive antenna materials (R_{cd}), and the other due to the radiated power (R_a). This can be written as follows:

$$Z_{in} = R_{in} + j\,X_{in} = R_{cd} + R_a + j\,X_a = R_{cd} + Z_a$$

where $X_a = X_{in}$. The part of input impedance indicated as Z_a is called *radiation impedance* and it only takes into account the power radiated and energy stored by the antenna. Moreover, R_a models the active power of the radiated fields and X_a the excess energy in the near field.

The antenna input impedance is related to another fundamental parameter, being the *reflection coefficient* Γ. Given $Z_g = R_g$, the real-valued impedance of the Thévenin voltage source applied at the TX antenna terminals, the reflection coefficient is defined as:

$$\Gamma = \frac{(Z_{in} - R_g)}{(Z_{in} + R_g)}$$

The reflection coefficient (coinciding with the single-port S-parameter of the antenna S_{11}) represents the fraction of the injected power that is being reflected at the TX antenna terminals, caused by impedance mismatch between the generator and the antenna. Often, in practice, the equivalent parameter called *return loss* (in dB) is used, defined as the inverse of the magnitude of the reflection coefficient, expressed in dB, i.e.:

$$RL|_{dB} = 20 \log_{10}(1/|\Gamma|)$$

The reflection coefficient and return loss are, in general, a function of the frequency. A typical design criterion requires that the reflection coefficient satisfies $|\Gamma| = |S_{11}| < -10$ *dB,* for $f_L < f < f_H$, meaning that less than 10% of the power injected at the antenna terminals may be reflected, over the frequency band $[f_L, f_H]$.

Gain and Directivity

The gain is defined as the ratio between the radiation intensities of the considered antenna and of an isotropic antenna, having the same injected power P_t at their terminals, for a given direction (θ, ϕ), i.e.:

$$G(\vartheta,\varphi) = \frac{U(\vartheta,\varphi)}{\frac{P_t}{4\pi}} = 4\pi \frac{U(\vartheta,\varphi)}{P_t}$$

In contrast, the directivity is defined as the ratio between the radiation intensity of the antenna under test and the radiation intensity of an isotropic radiator emitting a radiated power P_{rad}, along a given direction, i.e.:

$$D(\vartheta,\varphi) = 4\pi \frac{U(\vartheta,\varphi)}{P_{rad}}$$

In general, the power at the terminals of the antenna, P_t, and the radiated power P_{rad} are different, with $P_{rad} \leq P_t$, due to losses in the dielectric and conductive parts of the antenna. Such a relationship is expressed by the *conductive-dielectric efficiency* e_{cd}, being $P_{rad} = e_{cd} \cdot P_t$, with $0 < e_{cd} < 1$. Hence, the relation between gain and directivity is:

$$G(\vartheta,\varphi) = e_{cd}\, D(\vartheta,\varphi)$$

To characterize antennas, one usually measures the gain as a function of the angular direction, i.e. the *gain pattern*. This can be a full 3D pattern, for all directions (θ, ϕ) on the unit sphere, or a 2D gain pattern, representing a *cut* of the 3D pattern.

Radiation Patterns

The radiation pattern is defined as a mathematical function or a graphical representation of the far-field (i.e. for $r \gg 2D^2/\lambda$, with D being the largest dimension of the antenna) radiation properties of the antenna, as a function of the direction of departure of the EM wave. A radiation pattern can represent several quantities, such as gain, directivity, electric field or radiation vector. Consequently, the terms *gain pattern*, *electric field pattern* or *radiation vector pattern* are used, respectively.

The radiation patterns can be tridimensional, i.e. function of (θ, ϕ, r) or bidimensional. In the latter case the radiation pattern represents a *cut* of the 3D radiation pattern, for given angles $\theta = \theta_0$ or $\phi = \phi_0$. The 2D gain pattern of a λ/2 dipole antenna is shown as an example in Figure 3.

Figure 3: Vertical cut of the 3D gain pattern of a half-wavelength vertical dipole in free space (for φ = 0°)

Efficiency

The *total antenna efficiency* quantifies that fraction of the maximum power available at the generator that is radiated by the antenna in the surrounding space. The total power loss can be decomposed into two contributions, the *mismatch loss* and the *conductive-dielectric loss*. The first is the fraction of power that is reflected, hence lost, due to impedance mismatch between the generator and the antenna, indicated by $M_t = 1 - |\Gamma|^2$. The second loss contribution is due to the ohmic power dissipation in conductive and dielectric materials of the antenna. In the circuit representation in Figure 2 this corresponds to the power that is dissipated by the resistance R_{cd}, quantified by the conductive-dielectric efficiency e_{cd}. The radiated power is related to the maximal power that can be provided by the generator by

$$P_{rad} = M_t \, e_{cd} \, P_g = e_t \, P_g$$

where $e_t = M_t \, e_{cd}$ is the *total antenna efficiency*. In practical antenna measurements, the parameter that is commonly measured is called *radiation efficiency* e_{rad}, and coincides with e_{cd}.

Polarization

This parameter actually denotes *the polarization of the electric field radiated by the antenna*, along a given direction, in the far field zone. When the direction is not specified, the polarization refers to the direction of maximum gain. The field (electric or magnetic) radiated by the antenna in the Fraunhofer far field, can be seen as a locally-plane wave, propagating along the radial direction $\hat{z}$. While propagating, the field vector rotates in the plane perpendicular to $\hat{z}$, describing a figure that is, in general, an ellipse, as the one depicted in Figure 4. In that case, the polarization of the antenna is said to be *elliptical*. The polarization ellipse, describing the antenna polarization, is completely characterized by two parameters, being the *eccentricity* $\tau = OA/OB$, being the ratio between its minor and major axis, and the *tilt angle* α, between the major axis of the ellipse and the x axis of the local reference system, as shown in Figure 4. The *elliptical polarization* is the general case of polarization, with the *linear polarization (LP)* and *circular polarization (CP)* representing its particular cases.

In practice, the quality of polarization of an antenna is described by the *axial ratio* (AR), which provides the same information as the absolute value of the eccentricity $|\tau|$. The sign of τ represents the sense of rotation: if $\tau > 0$ we have a right-hand polarized (RHP) wave, while if $\tau < 0$ the sense is left handed (LHP). The axial ratio is defined for circular polarization and for linear polarization.

For linearly-polarized antennas, the *axial ratio for linear polarization* is used, defined as:

$$AR_{LP}|_{\mathrm{dB}}=20\,\log_{10}\left(\frac{1+|\tau|}{1-|\tau|}\right).$$

We have that $0 < AR_{LP}|_{dB} < +\infty$, with the value 0 corresponding to linear polarization, and $+\infty$ to circular polarization.

Figure 4: Polarization ellipse

Specific Absorption Rate (SAR)

The Specific Absorption Rate (SAR) expresses the energy absorption rate of an electromagnetic field impinging on human body tissue. It is defined as the time derivative (i.e. the speed) of the infinitesimal energy *dW*, absorbed by an infinitesimal portion of mass of tissue *dM,* that is

$$SAR = \frac{d}{dt}\frac{dW}{dM} = \frac{d}{dt}\frac{dW}{\rho\, dV} \qquad \left[\frac{\mathrm{W}}{\mathrm{Kg}}\right] \text{ or } \left[\frac{\mathrm{W}}{\mathrm{g}}\right]$$

with ρ being the mass density of the human tissue.
In practice, the SAR is calculated by determining (by measurements or simulations) the electric field E inside the human tissue and using the relationship

$$SAR = \frac{\sigma E^2}{\rho}$$

Moreover, the final value of SAR is obtained by averaging the local value on a given mass of human tissue.

2.2. Textile antenna design criteria and optimization

Typical design criteria

Usually, the goal of textile antenna design consists in determining the antenna geometry that meets some given design criteria, which are imposed on one or more of the described performance parameters.

Antenna design typically consists of a first stage, in which a rough calculation of the antenna dimensions is performed, by making use of analytical formulas (such as those for rectangular patch antennas, available in antenna theory textbooks). Next, the dimensions are fine-tuned (that is, *optimized)* in order to meet the design criteria. Optimization is performed automatically on a simulation model of the antenna, constructed by available full-wave electromagnetic solvers (such as ADS Momentum, Ansoft HFSS or CST Microwave studio). Antenna model and optimization should preferably include the wearer's human body, as this might substantially affect the antenna's performance. Simple models, such as a three-layer portion of the external human tissue, are sufficient when interested in SAR and impedance matching, while full human-body model must be necessarily used when radiation patterns need to be computed.

The typical design criteria on textile antennas are the following:

- *Resonance frequency(ies):* the application for which the antenna is intended will specify the frequency or multiple frequencies of resonance of the antenna. For example, ISM band antennas are required to resonate at one (or more) of the ISM frequencies (868 MHz, 2.45 GHz, 5.8 GHz). An antenna operation requires that the antenna's input impedance is optimally matched to the source impedance, thus the injected power is maximally converted to the form of radiated field. The concept of resonance is strictly related to the reflection coefficient, which is described next.

- *Reflection coefficient:* the typical design criterion, ensuring antenna resonance at a given frequency f_r, is

  $$|S_{11}| < -10\ \mathrm{dB}, \quad f_L \leq f \leq f_H,$$

  where $[f_L, f_H]$ is the *bandwidth*, usually chosen such that $f_r = (f_L + f_H)/2$.
  For antennas with dual input/output, next to the criteria on the reflection coefficient, imposed on both ports, also a criterion on the isolation between the ports is imposed, expressed in terms of the transmission coefficient between the two ports (i.e. S_{21}, S_{12}):

$$\begin{cases} |S_{ii}(f)| < -10 \text{ dB}, & i = 1,2 \\ |S_{ij}(f)| < -15 \text{ dB}, & i,j = 1,2, i \neq \text{j}' \end{cases} \quad f_L \leq f \leq f_H$$

- *Gain:* the typical requirement on the gain of a textile patch antenna is that the maximum of the gain pattern, $G(\theta_{max}, \phi_{max}) = G_{\max}$, has to be larger than a given value, for any frequency inside the bandwidth interval, that is:

$$G_{max} > G_{max,goal}, \quad f_L \leq f \leq f_H$$

- *Efficiency:* to maximize the radiated power, antenna designer will aim at a large radiation efficiency. As previously discussed, the total efficiency is the product of two terms. The first one, the impedance mismatch factor M_t, can be maximized by minimizing the reflection coefficient. The second term, the conductive-dielectric efficiency e_{cd}, can be maximized by using textile materials with low ohmic and dielectric losses, i.e. electrotextiles with high conductivity and textile dielectric substrates with low *tanδ.*

- *Polarization:* in some specific applications, a particular type of polarization may be required:
  - *Linear polarization* is straightforward to achieve, for example, by means of a simple rectangular patch with the feed point placed along one of the symmetry axes. In this case, the design criterion imposes an axial ratio (for linear polarization, as previously defined) typically smaller than 3 dB, for $f_L \leq f \leq f_H$.
  - *Circular polarization* is required in applications such as GPS satellite communication. In this case, an *axial ratio for circular polarization* is defined and a similar criterion as for linear polarization is applied:

$$AR_{CP}|_{\text{dB}} = 20 \log_{10}\left(\frac{1}{|\tau|}\right) < 3 \text{ dB}, \quad f_L \leq f \leq f_H$$

- *SAR:* Design criteria typically impose a SAR lower than the maximum limit, imposed by regulations. Several countries impose safety limits on the maximum level of allowed SAR. For example, such a limit is set to 2.0 mW/g (averaged on 10 g of tissue) in Europe.

  In textile antennas the presence of a ground plane, placed between the radiating element and the wearer's body, is in any case recommended because it acts as an EM shield for the body tissue and thus allows a considerable SAR decrease.

3. Challenges and adverse effects related to textile antennas

When dealing with wearable textile antennas, several *adverse effects,* which influence the performance characteristics, often occur. It is very important for the design engineer to be able to efficiently model these effects, in order to predict variations in antenna performance. The main adverse effects that are treated in the present literature on textile antennas are briefly summarized as follows.

3.1. Proximity of human body

The presence of the human body in close proximity of a wearable textile antenna is the most common cause of its performance degradation, since the radiator is integrated into garments and, hence, in close vicinity of the human wearer surface. Typically, wearable antennas are worn in the vicinity of arms, legs, chest or back of the human body, at maximum distances in the order of a few centimeters. This has an impact on the return loss, radiation patterns and radiation efficiency.

Basically, textile antennas can be subdivided into two categories, those having a ground plane (such as patch antennas) and those without (such as UWB dipoles). In the first case, the effect on performance is very small, since the ground plane acts as an electric shield between the radiating elements of the antenna and the human body.

For textile antennas without a ground plane, the presence of the human body produces substantial effects on the antenna performance because it acts as an absorber for the radiated field and represents an additional loading. This mainly alters the antenna input impedance and efficiency. Radiation patterns also change with respect to the free space situation: the human body acts as a lossy reflector, making the radiation pattern more directional in the “off-body” direction. An example of such a behavior, on a wearable antenna without ground plane, is shown in Figure 5, where the on-body and free-space horizontal pattern of a wearable UWB monopole antenna on a polyimide substrate (realized by the EM-group of Gent University), are compared.

Figure 5: Horizontal gain pattern of a wearable UWB monopole at 3.1 GHz: free-space vs. on-body comparison.

It is very advisable, especially in the case of wearable antennas without ground plane, to predict the effect of the human body during the design and optimization phase of the antenna. Alternatively, it is also very convenient to analyze human body proximity effects by means of simulations or measurements on real human subjects or human body phantoms.

3.2. Bending

Antenna bending represents another very important adverse effect to be taken into account when designing and analyzing wearable antennas. Since a textile antenna is flexible by nature, when integrated into a garment, typically in the arm, leg or chest region, it conforms to its surface. This phenomenon causes a remarkable variation of some performance parameters, being a shift of the resonance frequency and a deformation of the radiation pattern. For narrowband antennas, tuning of the resonance frequency on the operational band is of crucial importance to ensure maximal link quality and reliability. Therefore, it is very important for the design engineer, to be able to model and predict the effects of bending on textile antennas.

Textile antenna bending has been, in the last years, object of study of many researchers all over the world, and several types of approaches have been used: first, by means of measurements and full-wave simulations, and, more recently, by means of more sophisticated analytical- and stochastic-based models. Fundamental results were obtained by Boeykens *et al.*, who developed for the first time an accurate analytical model for cylindrically-bent textile rectangular patch antennas [13]. In such a model, the antenna substrate is treated as a cylindrical-rectangular cavity, for which the EM-fields distribution is expressed by solving Maxwell's equation inside the cavity, treating the bending radius as a parameter. Effects specific to textile materials, such as patch elongation due to stretching and substrate compression, are accounted for in the model, which is capable of accurately reproducing the measured resonance frequency as a function of the bending radius. After that, the analytical model was used by the same authors as a core element for a novel stochastic framework, based on the polynomial chaos theory, for the description of the statistical distribution of resonance frequency, when the bending radius is subjected to a random variation due to different body morphology of wearers [14].

3.3. Washing

Textile antennas are meant to be a fully integrated part of the future intelligent garments, and consequently they are prone to get dirty, because of dust and sweat. Thus, they will need to be washed, together with the garment or separately. For many years, the effects of washing have been neglected to the scientific community, which focused more on design and realization problematics. However, over the last years, some researchers have taken washing into consideration and studied the effect on performance stability after several washing cycles, as well as realization techniques to produce water and washing-proof antennas. Scarpello *et al.* [15] performed a valuable experimental study in 2012 on how machine-washing cycles affect performance of screen-printed textile antennas. In particular, two screen-printed inset-fed antenna prototypes were considered and their performance was compared. One antenna had a thermoplastic polyurethane waterproof coating (TPU), the other did not. Their figures of merit, being $|S_{11}|$ and e_{rad}, were studied before and after two washing cycles and compared to the ones of a similar antenna with a conventional *Flectron®* patch. It was experimentally proven that a screen-printed antenna with TPU coating exhibits the most stable performance, while the one made of a conventional electrotextile, without coating, undergoes a severe deterioration in performance after two washing cycles.

3.4. Power efficiency

For wearable systems, including textile antennas, power efficiency represents a crucial matter, especially for the so-called *autonomous systems*, where the necessary power for the system operation, is ideally obtained entirely by means of *energy harvesting* [16] from the surrounding environment, and no additional power supply is needed. Even in the case of wearable systems equipped with wearable battery units, it is very important to keep power consumption as low as possible. To this aim, several techniques were recently envisaged, by means of innovative textile antennas, such as *active antennas* as well as the use of multi-antenna processing techniques, such as *diversity* with multiple wearable antennas.

Active antennas

The concept of active antennas has been used for a long time with conventional antennas, and applied recently to textile wearable antennas. In recent contributions, novel textile antennas with integrated active circuitry have been proposed, achieving remarkably higher gains at low noise figures with a very compact and wearable structure. Using textile antennas that directly amplify the received signal, with little added noise, increases the power level of received signals in off-body wireless communications, without the need of increasing power levels at the transmit side. We make reference to the following Section for a more in-depth overview.

Diversity

A well-known adverse effect in body-centric communications is caused by fading and shadowing of a signal received by a moving subject, equipped with a wearable antenna system. These phenomena are a consequence of multipath propagation and have a negative effect on power consumption. In particular, these random fluctuations on the received signal produce an increase of the Bit Error Rate (BER).

To cope with this detrimental effect and guarantee a given level of BER at RX side, transmitted power has to be substantially increased with respect to the case without fading and shadowing which obviously does not represent a power efficient solution to the problem. Alternatively, a more intelligent, power-efficient approach consists in using multiple receiving wearable antennas, distributed over different locations on the human subject, implementing *diversity* [17]. This technique is based on the main principle that the probability of experiencing simultaneous very low RX signal levels on multiple antennas is substantially smaller than on a single antenna. Diversity is classified according to the characteristics that differentiate the multiple antenna signals from each other, in particular *space* (i.e. antenna location)*, frequency, pattern* and *polarization.*

Briefly, diversity allows to increase the RX signal level without any additional increase of TX power or, equivalently, to obtain the same received power as in the single RX antenna case, but at remarkably lower TX power. We describe example of state-of-the-art implementations of wearable antenna diversity techniques in the following section.

4. Overview of the state-of-the-art on textile antennas

In this section, we summarize and describe some of the most recently developed wearable textile antennas, constituting the current state-of-the-art in this field. Each of the described antennas possesses features that provide solutions to one or more of the adverse effects and challenges described in the previous section.

A classification is made here, according to the frequency band of operation, ranging from the lowest ISM band (868 MHz) to the recently explored 60 GHz band.

4.1. UHF bands for RFID ([860-960] MHz)

Radio-frequency Identification (RFID) technology aims at unambiguously identifying an object, having a unique ID-code, given by a device known as an RFID-tag. An RFID-tag consists of a small radio frequency transponder composed of an integrated circuit and an antenna. Such a device, when “interrogated” by a “reader”, answers by transmitting a radio frequency signal containing the information about its identity [18]. According to the international standardization, RFID technology makes use of UHF frequency bands. EPCglobal, responsible for such standardization activities, has set some standards in the UHF frequency range [860, 960] MHz [19], in which most of the developed RFID tags and antennas are operating.

Up to now, RFIDs have been widely used in applications such as tracking of goods, access management, and contactless payment. More recently, the newly introduced textile antennas have progressively gained attention as integrating component of wearable RFID tags, which has become a popular object of research, for applications in localization and tracking of persons. Since then, numerous textile antennas have been proposed, operating in the indicated frequency range. Here, we describe a few among the latest developments in this field.

In 2014, Koski *et al.* [20] presented an 866 MHz patch tag antenna using an anisotropic embroidered textile structure as radiating patch. The antenna performance is also compared to an equivalent prototype, having the radiating patch made of conventional copper fabric. Assessment of readability range was performed with the antenna mounted on the arm of a human test subject. Analysis showed that the wearable RFID antenna with embroidered patch exhibits comparable link loss and shadowing, with respect to the equivalent version with conventional copper patch, demonstrating the suitability of the embroidering technique in wearable RFID antenna manufacturing.

Hirvonen *et al.* [21] proposed in 2013 a textile monopole antenna, operating in the same frequency band (867 MHz), for on-body propagation. The on-body communication performance in terms of path loss was also experimentally investigated. The antenna is a 4 mm-thick monopole on a 50 x 50 mm-sized ground plane, whose conductive parts are made of silver-plated polyimide, exhibiting high flexibility and conductivity. The substrate is a 4 mm-thick dielectric with very low permittivity foam (ε_r).The antenna consists of two polygonal top plates, with optimized topologies, to which the feed is connected. The 3-D structure of this antenna is obtained by bending the electrotextile over the substrate. The radiating element is the 4-mm short, connecting the top plate with the bottom ground plane.

An electronics board including wireless electronics and batteries is also present, embedded into the antenna substrate. The antenna exhibits a rather small value of G_{max}, of about -10 dBi, due to the small dimensions and low conductivity of the textile material. However, measurements of the on-body link between two antenna prototypes worn on different body locations, showed relatively high values of on-body channel gains, ranging between -47 and -56 dB in anechoic environment, and between -35 and -80 dB in a multipath scenario (hallway). Hence, the antenna represents a suitable small-sized and reliable solution for on-body wireless communication.

In addition, research was recently performed on the integration of solar energy harvesters with planar textile antennas for the UHF RFID band. Declercq *et al.* [22] presented a novel wearable aperture-coupled shorted planar antenna, with solar cells directly integrated on top of the radiating patch. Such a solution allows space-efficient integration of two basic elements into a wearable textile system, being wearable antenna and energy harvester, forming a compact stacked structure.

The proposed antenna is designed to operate in the UHF frequency band [902, 928] MHz and features a shorting plane between radiating patch and ground plane, resulting in reduced patch dimensions, equal to 62 mm x 80 mm, with respect to conventional $\lambda/2$ patches. Aperture-coupled feeding, chosen to improve flexibility and robustness, is realized by means of a meandered microstrip line on the bottom side of the structure, coupled to the patch via an H-shaped slot in the ground plane. The substrates consist of an 11 mm-thick flexible polyurethane foam for the antenna, and a 0.95 mm-thick aramid layer for the feeding line. Two a-Si:H solar cells are mounted directly on the antenna patch. Their influence on the antenna radiation properties is negligible since their thickness of 0.2 mm is much smaller than the wavelength. The DC signal obtained by the illuminated solar cell is routed along a copper wire, the shorting wall serving as return path, to the back side of the structure, where an appropriate regulator circuit is integrated to provide stable voltage output. The performance of the antenna was experimentally tested when mounted on a real human subject, resulting in an impedance bandwidth of 64 MHz and a maximum gain of 1.6 dBi.

4.2. 2.45 GHz and 5.8 GHz ISM bands

Industrial, Scientific and Medical bands are reserved portions of the radio spectrum, defined by the ITU Radio Regulations [23], that are employed in body-centric wireless communication applications and, more in general, for other industrial, medical and scientific applications. The majority of textile antennas developed to date are intended for operation in some of those ISM bands, especially in the 2.45 GHz, by far the most popular for wearable antennas, and 5.8 GHz bands. The first band represents a good trade-off between antenna dimensions (inversely proportional to frequency) and path loss (increasing with frequency), whereas the second is more convenient when smaller antenna sizes are required. We now illustrate some representative examples of current state-of-the art antennas in these bands.

2.45 GHz

Hertleer *et al.* [24] introduced a wearable patch antenna for operation in the [2.4, 2.4835] GHz band, made of a shock-absorbing, fire-retardant foam substrate and suitable for rescue worker applications. The antenna employs a simple topology, consisting of a truncated-corner rectangular patch (see Figure 6), with coaxial feeding on the patch diagonal, allowing the excitation of two orthogonal modes that yield nearly circular polarization. The conductive parts of the antenna are composed of commercially available electrotextile materials, with very high conductivity, in particular "*ShieldIt*™" for the radiating patch and "*Flectron®*" for the ground plane. The proposed antenna was first designed by means of an optimization performed by a full-wave EM solver, then prototyped and tested in different operating conditions. In particular, the authors showed, through both measurements and simulations, how the proximity of a human arm over which the antenna was bent, affects its performance by producing a resonance frequency shift. However, thanks to the design's relatively large -10 dB impedance bandwidth, the antenna still meets the design requirements when bent around a human arm.

Figure 6: Schematic of the truncated-corner rectangular patch antenna

In 2008, using the same protective foam as a substrate, Vallozzi *et al.* [25] proposed a 2.45 GHz patch antenna with *dual polarization*, allowing to implement polarization diversity using a single, compact, wearable antenna. The antenna, shown in Fig.7, employs a simple nearly-square topology with a small slot in the center and with two coaxial feeds positioned symmetrically on the two patch diagonals. This allows the excitation of two orthogonal, linearly-polarized waves which can simultaneously transmit/receive two independent radio waves, for implementation of polarization diversity. Antenna design and optimization were first performed with the aid of a full-wave EM solver, then a prototype was constructed and its performance tested by measurements. In addition to a free space situation, measurements were also performed on a human body in order to verify the antenna's resilience to the presence of a human body. In both cases, the measured reflection coefficients meet the design requirements ($|S_{11}|<-10$ dB; $|S_{22}|<-10$ dB), with the resonance frequency undergoing only a very small shift in the on-body situation. Measured gain patterns also remain almost unchanged in the on-body case, with respect to the free-space situation, with the maximum value being about 6 dBi in the broadside direction, which is more than sufficient to establish a reliable off-body communication link. Elliptical polarization was obtained in an on-body situation, versus nearly linear polarization in a free-space scenario. In the on-body case, however, the two polarization ellipses remained quasi-orthogonal to each other, ensuring the independence of the two signals needed to obtain diversity gain.

Figure 7: Realized prototype of dual polarized patch antenna on foam substrate

To apply diversity in off-body communication, two such antennas can be integrated into a wearable textile system, worn on the front and back side of a human subject, realizing a 4th-order receive diversity communication link by combining both pattern and polarization diversity [26]. By means of a realistic measurement campaign, it was shown that the proposed diversity system achieves a dramatic improvement in terms of received Bit Error Rates (BER) in an off-body wireless communication link between a fixed transmitting base station and a receiving subject equipped with such an antenna system, moving into a typical indoor multipath environment.

More recently, a novel and promising technology, denominated as *Substrate Integrated Waveguide (SIW),* an already well-known fabrication technology for rigid printed circuit boards, was for the first time applied by Moro *et al*. to develop a wearable textile antenna for operation in the 2.45 GHz ISM band [27]. Such a kind of patch antenna answers to important requirements in off-body communications, such as suppression of undesired surface waves and a high level of shielding from the human body, even with a very small ground plane, high directivity and front-to-back ratio, as well as performance stability. The structure consists of a cavity-backed slot antenna on a flexible protective foam substrate, with electrotextiles (Flectron) metallization on both sides. The top layer consists of rectangular conductive layer with a dog-bone shaped slot, representing the radiating element, while on the bottom layer a 50 Ω grounded coplanar waveguide represents the feeding line. A rectangular cavity is formed inside the antenna substrate, by using eyelets as metallized holes, with an appropriate spacing distance between each other. All geometrical parameters were optimized by means of a commercial full-wave EM solver, and after that the antenna was prototyped by a low-cost production technique. An experimental verification of the antenna performance in free space showed that the antenna exhibits a reflection coefficient lower than -10 dB in a bandwidth of 165 MHz, including the complete 2.45 GHz ISM band, a maximum gain of 3.21 dBi at 2.45 GHz, and a radiation efficiency of 68%. Experiments were repeated with the antenna integrated on the back side of a body-worn firefighter jacket, showing that the performance deviates only slightly from the free-space state, with the maximum gain increasing to 4.9 dBi, owing to reflections by the human body. Effects of bending were also verified by simulations, resulting in a very small increase of resonance frequency for a bending radius of 10 cm, which does not compromise the overall performance in the operation band.

Later, the SIW cavity-backed slot antenna was used by Lemey *et al.* [28] as a starting point for the development of a novel energy-harvesting platform, obtained by solar cells and dedicated flexible circuitry, compactly integrated on the top and back surface of the SIW antenna structure, as depicted in Figure 8. More specifically, two a-Si:H-solar cells were applied on the top side of the SIW antenna, while the necessary circuitry for the management of the output DC power from the solar harvesters was integrated on the back side, and connected to the solar cells by means of wires routed through the eyelet holes.

The integrated circuits were composed of a Central Power Management System (CPMS) and a Low Power System (LPS), deployed on a flexible polyimide substrate on a ground plane, glued on the back side of the SIW. More details of the implementation are described in [28].

Figure 8: SIW cavity-backed slot antenna with integrated energy-harvesting platform.

Other two interesting compact structures for the implementation of wearable textile patch antennas operating at 2.45 GHz, were proposed and studied by Liu *et al.* in 2014 [29]. These antennas both reduced the size of a conventional structure by half, using electrical or magnetic symmetries. In particular, the first antenna, denominated *quarter-wave patch,* is built up by using the half of a rectangular patch, by placing a shorting wall providing electrical symmetry. The second antenna, the half-mode cavity, originates from a half-mode substrate-integrated cavity, where an open aperture placed on the substrate's symmetry plane enables to only use one half of the entire cavity. The authors first developed an analytical analysis of both structures. Next, they built accurate EM simulation models, reproducing the features of their real textile implementation. Both antennas are made out of a low-loss nonabsorbent microwave radome foam PF-4 (thickness h = 3.2 mm and ε_r = 1.06), with a ground plane with size 10 x 10 cm, and a half-square top conducting layer consisting of silver-coated fabric NCS95R-CR. The shorting sides (one on the symmetry plane for the quarter-wave antenna, and three on the peripheral sides for the half-mode) are realized by linear embroidery with a conductive thread, consisting of stitches with 1 mm spacing and a total of 5 passes. Through simulations, it was found that seam compression caused by stitching produces a resonance frequency shift with respect to the ideal planar case. Hence, such an effect needs to be included in the model to correctly predict resonance frequency and performance. Real prototypes of the two antennas were built and their performance was experimentally assessed obtaining operational bandwidths of 300 MHz and 130 MHz, and maximum gains of 5.3 dBi and 5.1 dBi, for the quarter-wave patch and half-mode cavity, respectively. Moreover, the effects of human body proximity on the performance parameters appeared to be indistinguishable, proving the good isolation properties of the ground plane.

5.8 MHz

With respect to other ISM frequency bands, the 5.8 GHz ISM band ([5.725, 5.875] GHz) received relatively less attention from the research community. Fewer contributors have proposed, up to date, wearable textile antennas operating only in the 5.8 GHz band. Only one example of a recently proposed radiator operating in such a band is highlighted here.

A wearable antenna for operation in the 5.8 GHz band (for HiperLAN/2 applications), completely made out of textiles, was proposed by Sankaralingam *et al.* [30]. It consists of a circular patch, made out of *Zelt* electrotextile, sewn on the top side of an insulating polyester fabric substrate (thickness h = 2.85 mm, ε_r = 1.44), and a Zelt ground plane on the bottom side of the substrate. Antenna design and optimization were performed by a commercial EM solver based on the method of moments, resulting in very compact overall dimensions. In particular, the ground plane measures 120 x 120 mm and the patch radius has an optimized value of a = 11.4 mm. Performance was assessed by means of simulations and measurements: the latter resulted in a resonance frequency of 5.91 GHz, a maximum off-body gain of about 11 dBi at 5.8 GHz, and an efficiency of 74%, making the proposed radiator a suitable candidate for off-body communication in the targeted application.

Dualband (2.45 GHz and 5.8 GHz)

Wearable antennas with dual-band operation capability received larger attention than single-band antennas for 5.8 GHz. In this section, some relevant contributions of the last years are summarized.

Agneessens *et al.* proposed in 2014 a novel half diamond dual-band textile antenna [31], using *half-mode substrate integrated waveguide technology* (HMSIW). In contrast to the 2.45 GHz HMSIW antenna [29], described in the previous section, this novel radiator is capable of accommodating both 2.45 GHz and 5.8 GHz, by using a very compact, wearable antenna element with robust on-body performance. For wearable antennas, SIW technology offers a higher level of human-body shielding with a smaller ground plane, compared to conventional patch antennas or EBG substrate patches [32], which require ground planes with much larger dimensions than the radiating element. The half diamond dual-band HMSIW, as shown in Figure 9, consists of a cavity-backed topology with a half-diamond shape, with the addition of two slots, realizing the two desired resonances. The design flow to obtain such a topology starts from a rectangular SIW cavity-backed slot antenna with eyelets on the perimeter, which is first reduced by the half through a virtual magnetic wall along the diagonal, subsequently miniaturized by adding an additional row of eyelets. The performance of a realized prototype was determined in anechoic environment, both stand-alone and in on-body configurations, yielding a measured -10 dB reflection coefficient bandwidth of 4.9% and 5.1%, maximum on-body gains of 4.4 and 5.7 dBi, and an efficiency of 72.8% and 85.6%, for the 2.4 GHz and 5.8 GHz bands, respectively. Moreover, the maximal SAR values of 0.55 and 0.90 W/Kg for 500 mW input power, obtained from measurements at 2.4 and 5.8 GHz, respectively, are lower than the limit value of 1.6 W/Kg (averaged over 1 g of tissue), imposed by international recommendations. Based on these results, this compact and low-cost antenna represents a convenient radiator, with excellent dualband performance and robustness, for use in body-centric applications, such as wearable biosensors for medical monitoring, or rescue workers' monitoring and coordination systems.

Figure 9: Half diamond dualband textile antenna prototype

In another recent publication by Mishra *et al.* [33], a wearable dual-band patch antenna with circular polarization is presented, constructed using conductive metalized nylon fabric (Zelt) for patch and ground plane, and a denim substrate. Its circular polarization outperforms linear polarization as it maximizes transmit/receive power, owing to its orientation independence. The topology consists of a modified rectangular slot patch antenna, with a particular L-shaped topology for the feed, with a surrounding coplanar ground separated from the feed by a peripheral slot, deployed on top of the substrate. The L-shaped feed line topology produces circular polarization by splitting the fundamental resonant mode (TM_{01}) into two degenerate orthogonal modes.

The antenna's slot topology, combined with the L-shaped feed, ensures a relatively wide impedance bandwidth around the two center frequencies, as well as wide axial ratio bandwidths for the circular polarization. In particular, simulation results showed large -10 dB $|S_{11}|$ bandwidths of 2017 MHz at 2.45 GHz and 1759 MHz at 5.8 GHz, and an axial ratio bandwidth of 800 MHz and 2343 MHz at 2.45 and 5.8 GHz, respectively. Simulated human body effects on the reflection coefficient resulted to be very moderate.

Experimental performance measurement yielded similar results, with a 5 dB upward shift on the $|S_{11}|$, around 2.45 GHz, due to fabrication tolerances. The presence of the human body produces a moderate deterioration of the measured performance. However, the operating bandwidth remains covered.

Another recently proposed multiband antenna, by Chen *et al.* [34] is capable of operating also in a third band located around 4.725 GHz, in addition to the two considered ISM bands. This is achieved by a modified U-slot topology for the patch, implemented in silver-coated nylon RIPSTOP fabric, on a flexible dielectric foam as a substrate material, with a ground plane on the bottom side.

4.3. Satellite communication bands: GPS, Galileo, Iridium

Wearable textile antennas are particularly convenient for satellite communications. For example, a useful application involves the coordination of activities by a group of rescue workers in operation. Each person may be equipped with a wearable textile system in which a textile antenna connects to a positioning satellite system, such as GPS, Galileo or the Global Navigation Satellite System (GNSS). By means of such antennas, each rescue worker can acquire information about his/her position, which can be forwarded to the base station that keeps track of the positions and allows optimal coordination of the team's activity.

Initial work on the design and implementation of a wearable textile GPS antenna, was performed by Vallozzi *et al.* in 2009 [35] . In this work, a wearable antenna for operation in the GPS-L1 frequency band [1.56342, 1.58742] GHz, was for the first time designed and implemented on a wearable protective-foam substrate, commonly used in rescue workers' clothing. The adopted antenna topology is a patch antenna with truncated-corner topology for the radiation element, as displayed in Figure 10, whose optimal dimensioning ensures right-hand circular polarization, as required by the GPS standard. The wearable materials employed for this antenna consist of high-conductivity elctrotextile Flectron®, for both radiating patch and ground plane, and a flexible shock-absorbing, fire-repellent foam for the substrate. The optimized dimensions for the radiating patch are about 8 x 8 cm, and the overall minimum ground plane dimensions are 12 x 12 cm, which can be considered sufficiently compact for wearable applications.

The antenna was first designed and optimized by means of the full-wave EM solver ADS Momentum®. Next, several prototypes were built. An experimental assessment of the antenna performance was carried out in the anechoic chamber, considering three different operating situations, being *stand-alone*, *with covering textiles* (on the radiating element) and integrated *into a jacket worn on human body.* Three performance parameters were experimentally verified, being reflection coefficient, gain pattern, and axial ratio (at broadside). In the stand-alone situation, three different prototypes showed a reflection coefficient ranging from 117.5 MHz to 145 MHz, a -3 dB axial ratio bandwidth of about 33 MHz around the center frequency, covering completely the GPS-L1 band, and a directional off-body gain pattern with maximum value of 5.43 dBi along broadside. In the other two operating conditions, i.e. with covering textiles and on-body, a slight degradation of the measured performance parameters was observed, yet still meeting sufficiently well the design criteria. This demonstrated the capability of such topology to establish a reliable reception of the GPS signal, while ensuring sufficient immunity to human body and garment proximity.

Figure 10: Realized prototype of wearable textile GPS antenna

Later, other, more sophisticated wearable antennas, with improved performance, were proposed for satellite-based communications. In particular, Kaivanto *et al.* [36] introduced in 2011 a wearable circularly polarized antenna for operation in both GPS and Iridium ([1621.35, 1626.50] MHz) satellite bands, thus serving for both positioning and communication purposes. Coverage of both bands is enabled by a relatively wide operational bandwidth, achieved by polygonal-shaped slot on square ring patch as a radiating element. The radiating patch is implemented on a substrate made out of flexible textiles such as Cordura and another ballistic textile with appropriate mechanical properties. Electrotextiles made of silver and copper-plated nylon fabric were employed for patch and ground plane. Experimental analysis proved the capability of the antenna to operate sufficiently well in both frequency bands, in terms of reflection coefficient, even under bending conditions, with Right Hand Circularly Polarization (RHCP) maintained over a 53 MHz band, under bending conditions. The (RHCP) gain values over the 3D sphere are comprised in the interval [-2.5, 7.5] dBic, with maximum boresight values of 5 dBic for the GPS band and 6 dBic for the Iridium band, in unbent situation. The measured axial ratio, at both frequency bands, is lower than 5 dB over a wide angular region around the zenith. In conclusion, such an antenna represents a suitable candidate for use in simultaneous use in GPS and Iridium satellite communication, with satisfactory performance. However, the use of a probe feed inherently puts a limitation on the achievable bandwidth, which can surely be enlarged by making use of more sophisticated feeding techniques.

A further improvement to this problem is represented by a recent contribution by Dierck *et al.* [37]. The proposed antenna, which enables dual-band operation in GPS and Iridium bands, is additionally equipped with an active circuit, containing a Low Noise Amplifier (LNA) chip, conveniently integrated on the feed plane on the back side of the structure, enhancing the overall performance. Moreover, in contrast to [36], in which the employed probe feed limits the mechanical robustness and bandwidth, the proposed antenna uses hybrid coupler in combination with an aperture-coupled feed, as shown in the scheme of Figure 11, yielding a wide -10 dB reflection coefficient bandwidth of 340 MHz, and a 3 dB AR circular-polarization bandwidth of about 183 MHz, which are much wider than any other wearable antenna at the same frequencies, found in current literature. The aperture-coupled feed also enhances the flexibility and mechanical robustness of the structure, since no metallic structures (like probes) are present. To the authors' knowledge, such an antenna represents the only active wearable antenna with an LNA chip and hybrid coupler compactly integrated into the antenna structure.

The structure consists of three metallization layers and two substrates, i.e. a polyurethane foam substrate for the radiating patch (material typically employed in shoulder pads of protective garments), and a 0.4 mm-thick aramid substrate for the feed circuit. The top layer is a rectangular radiating patch, etched on a copper-on-polyimide film. Between the two substrates, a ground plane is deployed, with two orthogonal rectangular apertures that realize coupling between feed and radiating patch. The feed structure consists of two orthogonal microstrip arms, connected to the LNA via a hybrid coupler, providing the necessary 90° phase-shift between the two signals injected to the feeding arms.

Figure 11: Scheme of the active wearable antenna for GPS and Iridium satellite communications

The performance of a realized prototype, in terms of reflection coefficient and gain (RHCP and LHCP), was extensively verified through measurements in anechoic environment, for different situations, i.e. for the active and passive antenna versions, and in three scenarios, being free space, under bending and integrated into a body-worn jacket.

Passive antenna evaluation resulted in an $|S_{11}|$ < -10 dB frequency band [1.512, 1.8] GHz in free space, which does not significantly vary when the antenna is bent along several directions or integrated into a protective jacket worn on a human subject, owing to the hybrid coupler feeding, which ensures a robust 50 Ω impedance matching. The antenna gain (in the broadside direction) as a function of frequency, exhibits a maximum of 5.5 dBi at 1.619 GHz, and undergoes a maximal variation of about 1 dB in the frequency band of interest. Bending and integration into a body-worn jacket cause a decrease of the maximum gain, which, in the worst case, is 2.5 dB lower than in the free-space situation. RHCP gain is nearly insensitive to bending and presence of human body and stays at least 5.6 dB larger than the LHCP, as desired for GPS applications.

As for the active antenna, measurement resulted in an $|S_{11}|$ < -10 dB frequency band of [1.36, 1.7] GHz, covering the all bands of interest. Reflection coefficient almost does not vary when the antenna is bent or worn, compared to the free-space scenario. The broadside gain as a maximum value of 25.43 dBi at 1.625 GHz for free-space, which is about 25 dB higher than for the passive version of the same antenna, and has maximum variations of 1 dB in the interval [1.558, 1.677] GHz. These values remain almost unaltered for the different scenarios, yet the maximum gain slightly degrades, especially when the antenna is bent. RHCP gain remains, in any situation, at least 10.44 dB larger than the LHCP gain, over the whole frequency band of interest.

In conclusion, this antenna represents the state of the art in terms of performance and robustness, for wearable use and operation in both GPS and Iridium bands.

4.4. Ultra Wide Band (UWB)

Since the allocation of the UWB frequency bands by the Federal Communication Commission (FCC) in the USA ([3.1, 10.6] GHz), and by the European Commission (EU) in Europe ([6, 8.5] GHz), extensive research started on the design and prototyping of antennas for operation in such frequencies. UWB communication potentially offers several advantages with respect to conventional narrowband ones, such as higher achievable data rates and increased immunity to interference due to lower spectral power density. Also for body-centric communication, the advantages of UWB are particularly appealing, and this stimulated extensive research on novel UWB wearable textile antennas during the last decade. Here, we illustrate two most representative examples of recent state-of-the-art UWB wearable antennas. In both examples, a challenging requirement for UWB wearable antenna has been satisfied, that is the presence of a ground-plane between the radiating elements and the body of the wearer, which directs the radiation away from the human body. This feature represents a novelty with respect to formerly proposed wearable textile UWB antennas, based mostly on the very popular Vivaldi topology, which suffers from omnidirectional radiation pattern characteristics, in which a large part of the radiated power is absorbed by the human body, like in [38, 39].

In 2014, Zaric *et al.* [40] proposed a wearable UWB antenna with very compact profile unidirectional radiation pattern and high-fidelity performance, for operation in the EU UWB band ([6, 8.5]) GHz. The antenna is suitable for impulse radio UWB application (IR-UWB) for accurate localization of human subjects. The proposed structure, displayed in Figure 12 is, strictly speaking, non-textile. However, its very compact dimensions and low profile, as well as its high resilience to human body proximity, make it a wearable antenna. In future implementations, actual rigid materials could easily be replaced by electrotextiles and wearable dielectrics. The antenna consists of three metallization layers on two stacked low-cost FR4 substrates, with thickness h = 1.46 mm. The top metallization layer, which is the main radiating element, is a circular patch creating resonances in the higher portion of the considered band. A second metallization layer, placed underneath the first one, between the two substrate layers, has a triangular shape, ensuring the lower frequency resonance. The third metallization layer, below the whole structure, is a ground plane with the overall dimensions of 37 x 21 mm. Shorting pins, connecting the radiating elements and the ground plane, widen the $|S_{11}|$ bandwidth and connect the resonances at the different frequencies. Numerical and experimental characterization resulted in $|S_{11}| < -10$ dB and unidirectional radiation patterns with maximum values of about 6 dBi, in the whole band of interest. Time-domain characterization proved that the fidelity factor is higher than 95% for most off-body solid angles, outperforming most of the antennas previously reported in literature. Moreover, such an antenna is very robust to the presence of the human body, since the performance remains stable even when it is placed in direct contact of the human skin.

Figure 12: Realized low-profile UWB antenna with directional radiation pattern

Another full-textile UWB antenna, with ground plane and unidirectional radiation pattern, was envisioned by Samal *et al.* [41] in 2014. This antenna consists of a planar patch structure on a textile substrate made of felt. Ground plane and radiating patch are realized using a popular electrotextile material, denominated ShieldIt$^{\text{TM}}$. The proposed device represents the first all-textile UWB antenna with a full ground plane and a directional radiation pattern to be realized. This was achieved by a complex patch topology, consisting of the combination of several geometrical shapes creating several resonances at different frequencies, in order to obtain $|S_{11}| < -10$ dB over the complete FCC UWB frequency band ([3.1, 10.6] GHz). Experimental verification showed satisfactory performance, such as a maximum achievable gain of 6.89 dBi, very low radiation power radiated in the half space pointing to the human body, and insensitivity to human body proximity, making the antenna an excellent candidate for UWB off-body communications.

4.5. 60 GHz band

In the last few years, millimeter-wave body-centric communication around the central frequency of 60 GHz, started to receive considerable attention from the research community, owing to several inherent advantages. In [42], Chahat *et al.* report three main advantages. First, higher data rates may be achieved, given the wide available frequency spectrum of 7 GHz ([57, 64] GHz) worldwide. Second, the possibility to use lower power spectral density in wireless communication in this wide frequency band, results in a high level of interference resilience and high level of security. Finally, antenna sizes are drastically reduced, which is particularly appealing for wearable applications. In [42, 43], the same authors propose two interesting examples for 60 GHz wearable antennas.

The first one is a four-element patch antenna array, for off-body communication in the 60 GHz band. The antenna radiating elements were fabricated by laser cutting a 0.07 mm-thick flexible copper foil, deployed on a cotton substrate with a *ShieldIt*^{TM} ground plane. Antenna performance was experimentally tested in free space and in on-body conditions, as well as under bending and crumpling. In free space, the measured $|S_{11}|$ remains lower than 10 dBi in the 57-64 GHz range, and maximum measured gain at 60 GHz amounts to 8.0 dBi. The performance varies only slightly when the antenna is deployed on a human body, because the ground plane isolates it from the human tissue, and also under bending and crumpling.

The second proposed antenna for on-body communication is a planar Yagi-Uda, providing end-fire radiation for on-body propagation. In free space, the antenna is matched over the complete 60 GHz band and exhibits a maximum gain of 11.8 dBi at 60 GHz. Human body proximity affects performance depending on the antenna-body separation distance. However, the antenna performs in a satisfactory way also when deployed on a human subject, as well as under bending conditions.

5. Conclusions and future outlook

In this chapter, an overview of some representative state-of-the art wearable textile antennas is presented, based on the frequency range in which they operate. During the last decade, wearable antennas technology has evolved from simple rectangular patch narrowband antennas, to more complex topologies for the radiating element, with broadband characteristics, as well as new materials and promising technological solutions. This enables the fabrication of more robust, comfortable and seamless antenna structures. Wearable textile antennas are now available for many different operating frequencies, ranging from lower UHF bands to the most recent millimeter-wave band of 60 GHz. A lot of challenges related to body-centric communication and the presence of the human body, such as insensitivity and robustness to the wearer's body, bending, and washing have been tackled and successful solutions have been suggested.

Body-centric wireless communications still represents a popular field of research, together with wearable textile antennas. Future research work might focus on newer structures and topologies providing better performance, as well as on material and practical implementation issues. For instance, mechanical robustness and comfort are still remaining challenges and lots of research might be performed to achieve complete integration into garments.

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