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Wearable Antennas: A Review of Materials, Structures, and Innovative Features for Autonomous Communication and Sensing

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ABSTRACT Wearable antennas have gained much attention in recent years due to their attractive features and possibilities in enabling lightweight, flexible, low cost, and portable wireless communication and sensing. Such antennas need to be conformal when used on different parts of the human body, thus need to be implemented using flexible materials and designed in a low profile structure. Ultimately, these antennas need to be capable of operating with minimum degradation in proximity to the human body. Such requirements render the design of wearable antennas challenging, especially when considering aspects such as their size compactness, effects of structural deformation and coupling to the body, and fabrication complexity and accuracy. Despite slight variations in severity according to applications, most of these issues exist in the context of body-worn implementation. This review aims to present different challenges and issues in designing wearable antennas, their material selection, and fabrication techniques. More importantly, recent innovative methods in back radiations reduction techniques, circular polarization (CP) generation methods, dual polarization techniques, and providing additional robustness against environmental effects are first presented. This is followed by a discussion of innovative features and their respective methods in alleviating these issues recently proposed by the scientific community researching in this field.

INDEX TERMS Wearable devices, Internet of Things (IoT), wearable antennas, flexible, reconfigurable antennas, energy harvesting for wearable devices, specific absorption rate (SAR).

I. INTRODUCTION

The Fifth Generation (5G) network is a promising technology which will not only fulfill this exponentially increasing data rate requirement for mobile terminals, but also will enable integration with various services [1]. The overview of different technologies used in future 5G networks can be seen in Figure 1.

IoT is another technology foreseen to be enabled by the full deployment of 5G networks, wirelessly interconnecting all ''things,'' from household equipment to daily consumer devices. According to forecasts from Ericsson [4], it is estimated that about 28 billion smart devices will be connected across the global world by 2021 using legacy technologies and new wireless RF formats. Such connections will be the major enabler for applications in consumer electronics, building security and automation. A substantial portion of the consumer electronics segment is envisioned to be implemented as part of consumer outfits.

Wearable devices are expected to be an integral part of the Internet of Things (IoT) [3] (see Figure 2). According to Cisco annual report of Virtual Networking Index (VNI, 2014-2019) [5], the amount of traffic from wearable devices will increase to 277 petabytes per month by 2019, and the number of wearable devices will rise to 578 million in 2019. This is a five-fold increase compared to devices in 2014. Wearable devices are those which can be worn by a person and have the capability to connect with each other directly or through embedded cellular connectivity. They communicate with external devices through their embedded wireless modules, which interoperates with other components such as a battery, sensors, and antenna. Antennas in one of the most

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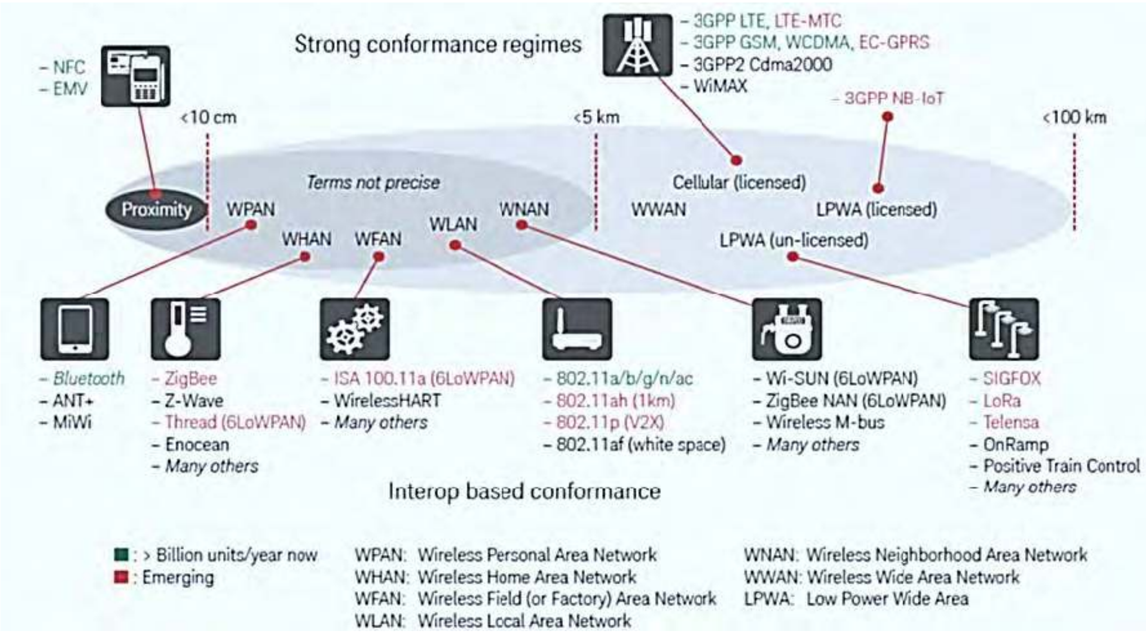


FIGURE 1. Overview of the different technologies used in future 5G networks [2].

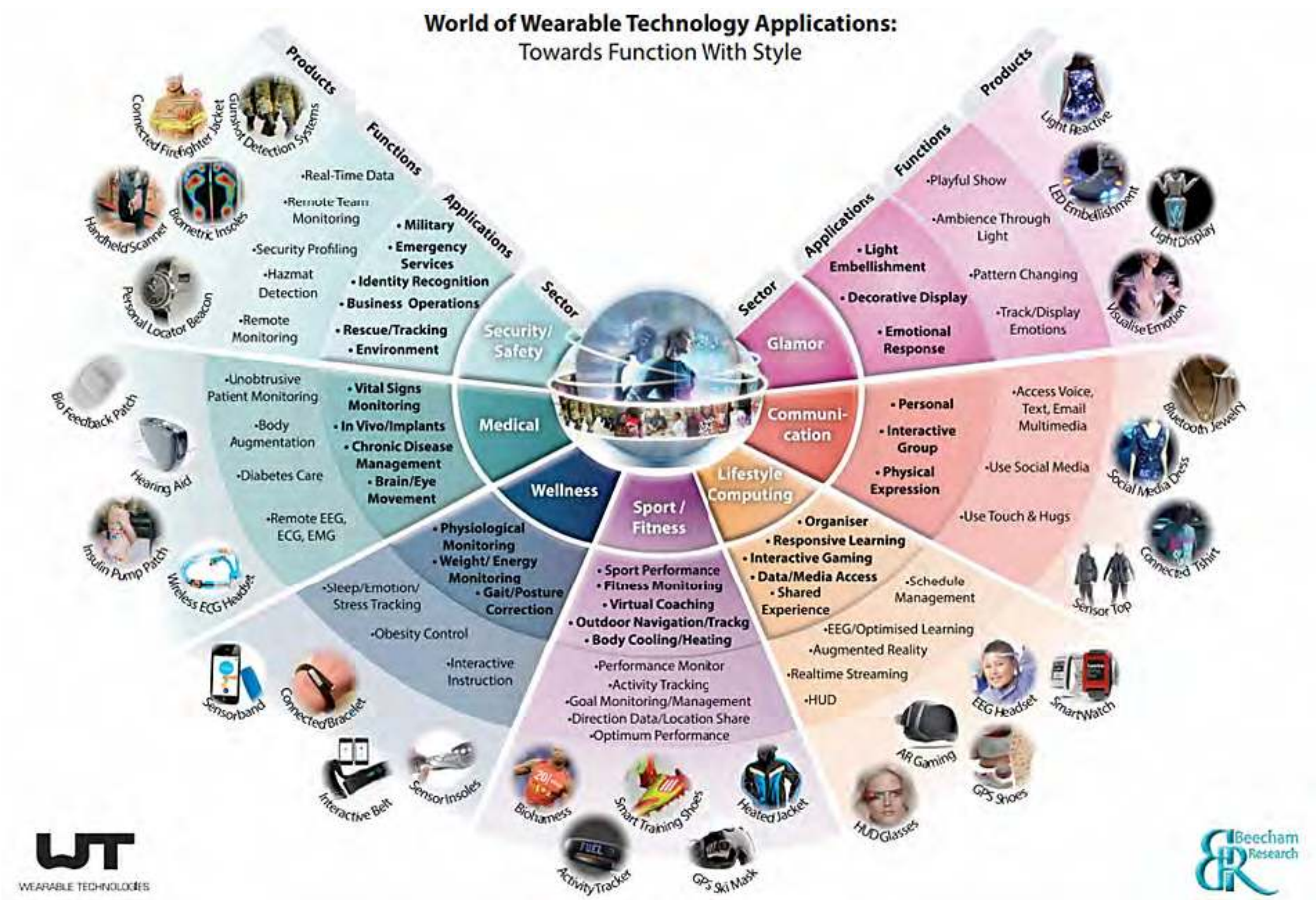


FIGURE 2. World of wearable technology [3].

TABLE 1. The wearable devices and their applications [8].

Field	Applications
Health Care	Glucose monitoring/Endoscopy/Oximetry/GPS tracker/Breast Cancer Detection/Wearable Doppler Unit/Wearable Thermometer.
Entertainment	Smartwatches/music Jackets/LED dress/intelligent shoes.
Rescue & Security	Helmet/Trackers/Fitness bands/E-shoes/Rain coat/Life Jackets.

significant components in wearable devices as they contribute to the overall efficiency of a wearable wireless link.

Wearables have diverse applications in our daily life. They are not limited to wristwatches, fitness bands, augmented reality glasses, but also encompasses many medical applications [6], [7]. In the field of healthcare, wearable devices are used to monitor critical health conditions of the patients. They include a glucose monitoring system to monitor the sugar level of the patient; capsule endoscopy to examine the inner intestinal system; wearable doppler unit and thermometer to monitor heartbeat; blood pressure and temperature of the body. Wearables are also used in entertainment and rescue operations. Examples of them include the glasses for augmented reality, smartwatches as touch-screen computer. Figure 2 shows a pictorial view of several wearables used in the entertainment segment. Besides that, wearable devices can also be integrated into jackets, shoes, rain coats, and helmets in rescue and emergency response systems. A brief overview of these applications is provided in Table 1.

Several aspects need to be considered when designing wearable antennas for use as a part of wearers outfit. They need to be unobtrusive, flexible and operate with minimum degradation in proximity to the human body [9]. Wearable antennas are also challenging in terms of fabrication - the availability of space on specific body locations, the effects of the host body, and performance degradation due to structural deformation are issues that need to be considered in the design process.

The title reflects the two main potential applications where wearable antennas can be most useful - for the purposes of communication and location sensing. To do so efficiently, and to enable wide acceptance of use, it is imperative that wearable antennas need to be enhanced with several key features, as specified in the sub-headings: they ideally need to be miniaturized to support operation in the lower (VHF, UHF) frequencies, need to be circularly-polarized to support satellite-based location sensing when used outdoors, need to be switchable to cater to on- and off-body communication using a single antenna, and finally, to be autonomous in terms of battery life – which can be solved with the integration of effective energy harvesting mechanisms. In this review, the issues related to wearable antennas will be addressed, and their effects investigated.

II. FLEXIBLE MATERIALS FOR WEARABLE ANTENNAS

Wearable antennas are built using different kind of conductive and dielectric materials. These materials are carefully chosen to provide a reasonable amount of mechanical deformations (bending, twisting, and, wrapping) with minimal influence based on different weather conditions (rain, snow, ice, etc.) and proper EM radiation protection. Recently, other types of fabric/nonfabric materials have been used for wearable antennas. For the case of fabric materials usage, the proper characterization of these textiles is essential [10]. On the other hand, the use of nonfabric flexible polymer-based materials such as Kapton, Polyethylene terephthalate (PET), and Polyethylene naphtholate (PEN) substrates come with predefined stable dielectric properties.

A. CONDUCTIVE (NANO) MATERIALS

Generally, for flexible antennas, the conductivity of the radiating part must be high, whereas the substrate (textile fabric/polymer film) must be constant in thickness. Besides that, low permittivity (ε_r) and loss tangent ($\tan \delta$) are preferred. It is well-known that the electro-textile antenna has less gain, efficiency, and bandwidth in comparison to its copper counterpart due to its relatively lower conductivity. Nickel-plated (corrosion resistant), silver plated (strong and flexible), Flectron (Copper-coated nylon fabric), and Nora conductive fabrics are several examples of these electro-textiles featuring different sheet resistances [11]. Similar to conductive polymer composite materials [12], providing high conductivity in electro-textile materials is the primary challenge in enabling continuous conduction current paths to minimize resistance losses and, hence, increasing antenna radiation efficiency. A comprehensive review of textile material can be seen in [13], [14].

On the other hand, polymer-based conductive materials loaded with conductive nanoparticles such as copper, silver, and gold are also gaining interest due to their high tensile strength, fabrication viability and hydrophobic properties [15]. The performance of antennas made from conductive polymers is also degraded at a minimal amount when stretched, as opposed to the woven/embroidered textile antenna [16]. Carbon nanotube, graphene nanofibers, and silver nanoparticles are increasingly being used to provide additional tensile strength and flexibility to the existing polymer-based substrates such as Polydimethylsiloxane (PDMS) [17]. Besides their high conductivity, they can be easily integrated into these polymer materials without significant additional cost in everyday outfits. Recently, conductive fibers embedded into the polymer substrate has been proposed with all lumped elements encapsulated within the PDMS layer to realize washable and physically robust wearable antennas [18].

Moreover, antennas with conductive transparent material are desirable for unobtrusive antenna placement on various wearable devices. Different materials such as oxides doped with Indium, conductive coated film, the combination of

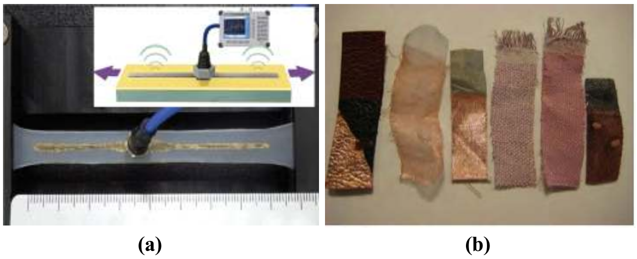


FIGURE 3. **(a) Conductive composite materials [15], (b) different conductive textile materials [11].**

TABLE 2. **The flexible conductive materials with their thickness and conductivity.**

Conductive material	Thickness t (mm)	conductivity σ(S/m)
EgaIn liquid fillet[21]	0.08	$2.5\text{x}10^5$
polyleurethene-nanopartical composite sheet[17]	0.0065	$1.1\text{x}10^6$
Zoflex+copper[22]	0.175	$1.93\text{x}10^5$
Silver flakes +Fluorine rubber[23]	N.A	$8.5\text{x}10^4$
AgNW/PDMS[24]	0.5	$8.1\text{x}10^5$
copper coated taffetta[25]	0.15	$3.4\text{x}10^6$
PANI/CCo composite[26]	0.075	$7.3\text{x}10^3$
Meshed fabric[19]	0.057	$2 \text{ x } 10^5$

silver and tin, fluorine, zinc, and aluminum, transparent fabric tissues, and mesh wired films are widely used to improve efficiency for transparent antennas [19], [20].

Textile and flexible antennas are also susceptible to stretching. Due to frequent deformable conditions in wearables, stretchable conductive materials have gained much attention among the innovators [23]. The main drawback of stretchable wearable antennas is their low radiation efficiency when being stretched [27]. To overcome this deficiency, different stretchable conductive materials exploits various conductive doping materials, for example, silver flakes embedded silicone [24], [28], silver loaded fluorine rubber [23], CNT based films [29], liquid metals in stretchable substrate [21], and more importantly the use of stretchable fabric itself [15], [30] (see Figure 4).

B. SUBSTRATES

The substrate used in wearable antenna has paramount importance in term of wearability, operation, and fabrication. Most flexible substrates used are low in permittivity and loss tangent. This is to increase their efficiency in the presence of the human body, at the cost of larger antenna size. Felt, fleece, silk, and Cardura are few examples of them. The measured dielectric values of different textile fabrics were provided in [31]. Other investigations such as in [32] have also presented a complete inkjet-printed localization tracking system on different kind of substrates for the wearable application.

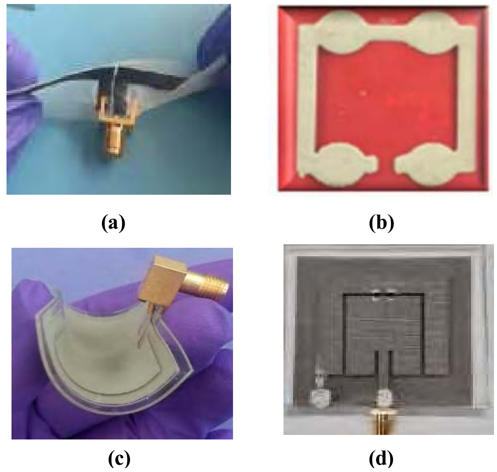


FIGURE 4. **(a) Lycra fabric on porous film [29], (b)silver fluorine rubber on elastomeric substrate [23], (c) AgNW embedded PDMS [24], and (d) fabric embedded PDMS [18].**

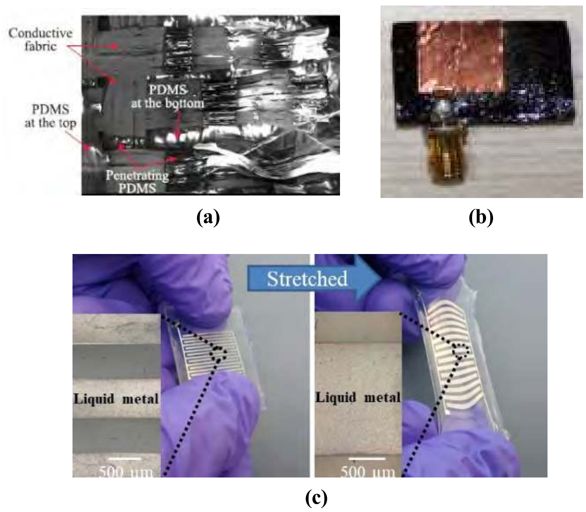


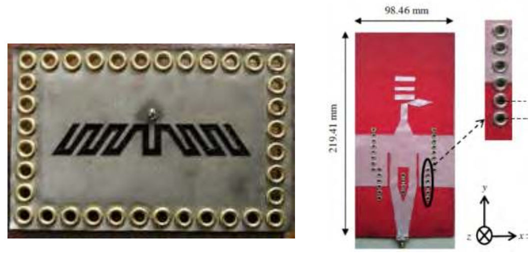
FIGURE 5. **(a) PDMS-ceramic composite [25], (b) magneto dielectric substrate [33], (c) Stretchable PDMS [34].**

Meanwhile, the effects of different flexible substrate parameters on the performance of a patch antenna were investigated in [13], [33]. In [33], the researchers examined the magnetodielectric flexible material properties under both flat and bending conditions. The flexible substrate exhibits high efficiency, adequate gain and stable radiation pattern without affecting bandwidth at bending condition.

The polymer-based substrate is also attractive in recent years due to their robustness, flexibility, wettability, and stretchability [25], [34]. In [25], a polymer based fabric was proposed by encapsulating fabric in the mouldable PDMS to solve the problem of weak PDMS-metal adhesion. Moreover, by adding low loss and high permittivity $SrTiO_3$ ceramic powder, the antenna size is reduced by up to 50 %, as shown

TABLE 3. Types of flexible conductive materials, their thicknesses and conductivities.

Dielectric material	Dielectric constant (ε_r)	Dielectric loss (tan δ)
Mn doped Zinc ferrite(0.2 %)[33]	7.5	0.025
PDMS-ceramic composite[25]	6.25	0.02
PDMS[22]	3.2	0.01
EVA[35]	2.8	0.002



(a) (b)

FIGURE 6. (a) SIW antenna on wolen substrate [46], (b) Yagi antenna on felt substrate [45].

in Figure 5(a). Next, a highly stretchable antenna has been fabricated using a multilayered copper coated rubber-PDMS sheets in [22]. More recently, as shown in Figure 5(c), the work in [34] proposed a highly stretchable PDMS layer by using plasma bonding technique. Several other variations of this polymer substrate have been mixed or modified to realize highly stretchable dielectric substrates. Next, a smart composite antenna has been proposed in [35]. This antenna is fabricated using *Ag* conductive elastomeric cloth as its radiator and ethyl vinyl acetate (EVA) as the dielectric substrate. The antenna showed a high radiation efficiency of up to 96.98% even after being stretched 25 % when operating in the C band. A summary of the different flexible materials and their dielectric values are summarized in Table 3.

To summarize, the choice of materials is significantly important in the realization of wearable antennas. Due to their conformal behavior, flexible materials have gained immense interest in place of rigid substrates. These flexible materials can be carefully chosen to withstand the physical deformation conditions such as bending, stretching, and even twisting while maintaining users' comfort. Wearable antennas also basically require low-loss dielectric materials as their substrate and highly conductive materials as conductors for efficient EM radiation reception/transmission. These highly conductive materials include copper, conductive fabric, metallic inks, conductive polymers and polydimethylsiloxane (PDMS) embedded conductive fiber. Meanwhile, the recent flexible substrates being introduced for wearable antennas includes the likes of Kapton, PET, liquid crystal polymer, organic material, ferrite magnetic materials, fabrics, and paper due to their unique properties.

III. FABRICATION TECHNIQUES FOR WEARABLE ANTENNAS

Fabrication methods are the determinants of the speed and accuracy of low cost wearable antenna prototypes. Mainly dependent on the choice of material, the most common wearable fabrication techniques include wet-etching [36], inkjet printing [37], screen printing [31], and embroidery methods [38]. These techniques are being employed in the fabrication of antennas to ensure low cost, durability, and comfort to the wearers in their daily outfits. A good overview of these fabrication techniques is provided in [39]– [41], with several more important ones discussed below.

A. SUBSTRATE INTEGRATED WAVEGUIDES (SIW) BASED TECHNOLOGY

A relatively new method to fabricate a wearable system on one platform is Substrate Integrated Waveguide (*SIW*). It is highly desirable to realize future System on Substrate (SoS) platforms for developing cost-effective, and easy-to-fabricate components for communication front-ends compatible with high-performance mm-wave systems [42]. This structure ensures the confinement of electric fields inside the cavity by the use of shorting vias on its side walls, backed by the full ground plane. This increases the quality factor of the structure, simultaneously improving isolation between the antenna and wearers body. This aspect is explained in [43] when introducing the design of two antennas placed on the same substrate on a wearer's garment. Next, the work in [44] proposed a multiband wearable antenna on a leather substrate. The copper sheet used to form the radiator was glued onto this substrate to enable operation in the Wi-Fi, WiMAX, and military bands. In [45], a pure copper taffeta fabric etched on a woolen felt substrate is used to realize low-cost wide band wearable antenna with radiation efficeincy more than 84% and fractional bandwidth of 46%. Next, matematerial inspired ultracompact SIW textile antenna has been proposed on same woolen felt substrat using conductive fabric in [46]. On-body measurements of the antenna exhibited radiation efficiecny of 74.5% with size reductioin of 80% as compared to similar structures. The antenna indicated satisfactory performance with low back radiation towards wearer's body. Besides that, recent antennas using this fabrication method are presented in [44]– [47] (see Figure 6).

B. STITCHING AND EMBROIDERY

Using the conventional method, a conductive textile yarn can be used to weave or knit the conductive patterns of the antenna before being attached or secured onto any non-conductive textile substrate [38]. Alternately, these antennas can also be directly embroidered onto the non-conductive textile fabric using a computer-aided embroidery machine. For example, conductive yarns have been used to weave the

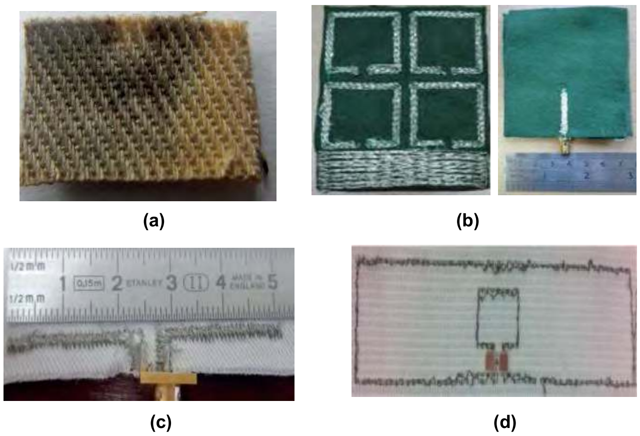


FIGURE 7. (a) silver deposited cotton [30], (b) Embroidered EBG backed antenna [50], (c) Satin filled pattern dipole [51], and (d) embroidered tag on elastic band [52].

radiating elements of the antenna on textile fabrics using traditional digital embroidery machines [38]. This technique was demonstrated when fabricating a wearable patch antenna for E-tag application in [48]. The radiating patch is connected to the ground as well as with an RFID chip, solely using conductive thread and sewing machine. The use of the e-textile conductive fabric resulted in improved performance in comparison to the same antenna fabricated using copper tape. More recently, a spiral circular polarized antenna with a wide axial ratio (AR) bandwidth was proposed in [49]. Elektrisola e-threads was embroidered on a Kevlar substrate using a high precision sewing machine.

The performance of the wearable antenna can be enhanced with reduced SAR values using a Split Ring Resonator (SRR) unit cell array. This was demonstrated in [50], which implemented such structure onto an embroidered monopole antenna, as illustrated in Figure 7(b). The fully embroidered EBG backed antenna, using the stitch density pattern performed well with a gain of 7.19 dBi and radiation efficiency of 67.9 % when calculated over the ear of the human voxel model. More recently, another dipole antenna using satin fill and contour fill stitch patterns have been compared in [51] for wireless body area network (WBAN) applications. It has been observed that satin pattern, due to its high accuracy in term of dimension, resulted in a consistent resonant frequency. On the other hand, due to better alignment between thread direction and current flow, the contour fill pattern exhibited minimized conducting losses when the same antenna structure was fabricated with the same stitch density. Meanwhile, an embroidered RFID tag using satin fill pattern on elastic fabric has been proposed in [52]. As shown in Figure 7(d), the range of the tag is reported to be increased compared to the same tag embroidered on a cotton substrate due to the hydrophilic behavior of the elastic band.

In [30], a new method has been proposed to deposit the silver nanoparticle layer within the textile breathable substrate at low curing temperatures (see Figure7(a)).

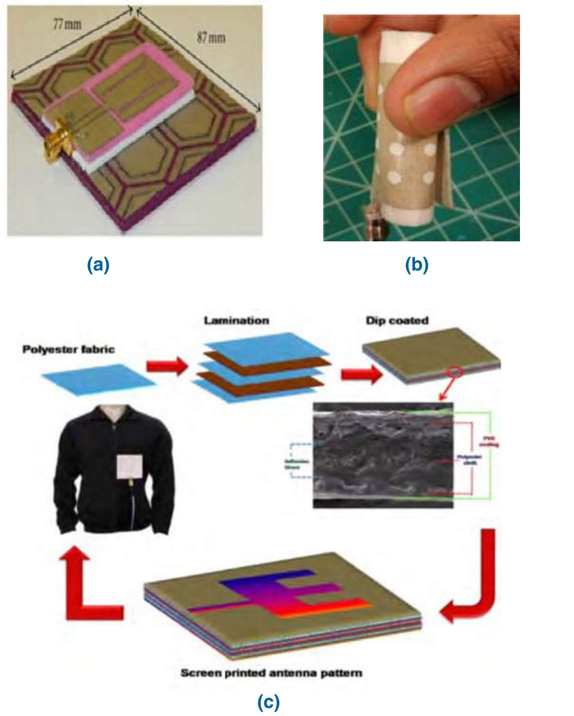


FIGURE 8. (a)Textile antenna with AMC [49], Porous patch antenna [54], and (c) Schematic fabrication process for multilayer fabrication [31].

The surface resistance of as low as 0.2 Ω/square was obtained using the technique. It is pertinent to note that the low-temperature curing temperature ($<60C^0$) is highly desirable for a flexible material having a low glass transition temperature.

The strength and flexibility of the conductive yarns, the accuracy of the embroidery machine, stitching density and direction on the fabric are several main parameters of concern in designing efficient antenna design using such method [39].

C. SCREEN PRINTING

The screen printing method is also another viable solution for the low-cost fabrication of wearable antennas. In this manufacturing method, the ink is pressed through a screen by using a blade. The screen consists of a mesh of fabric threads whose nonimage areas are blocked out using a stencil (emulsion) whereas, in the image areas, the screen is left open [53]. For instance, an E-shape antenna has been screen printed on a multi-layered polyester fabric in [31]. The water-resistant characteristic of the fabric provided a more efficient antenna for wearable applications, with a measured gain of 3.5 dBi for WiMAX application. A schematic diagram of this fabrication process is shown in Figure 8(c). Meanwhile, a highly efficient patch antenna was fabricated in [55] using this method, achieving up to 0.5 Ω/square of sheet resistance. Besides that, a highly conductive radiating part forming the patch antenna can be fabricated using composite materials (i.e., PDMS, graphene, and polyaniline (PANI) on a textile substrate as reported in [56]. More recently, screen printed flexible and

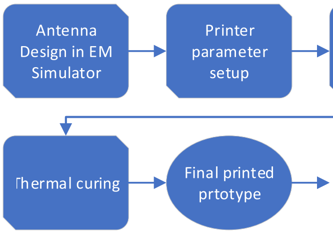


FIGURE 9. Flowchart of the process of inkjet printing [60].

(a) (b)

FIGURE 10. (a) Commercial DMP 2831 ink jet printer, (b) Setup of Inkjet printing with simultaneous sintering process on the textile substrate [63].

breathable antenna has been proposed on Evolon nonwoven substrate, which allows the conductive ink to be evenly distributed on the substrate [54]. The porous polyurethane web was used to make antenna durable and washable while minimizing the moisture effects on the antenna performance.

As a summary, despite being simple, the screen printing technology faces several limitations. They include its low-printing resolution, the limited number of realizable layers and lack of thickness control for the conductive layer. These factors resulted in the limited implementation of such technique, as the printing technology for wearables require better precision for proper operation of communication front-ends.

D. INKJET PRINTING

Inkjet printing is one of the preferred fabrication techniques on flexible substrates such as Kapton, PET, and Basalt due to its accuracy and rapid prototyping speed antennas [57]– [59]. In this method, conductive nanoparticle ink droplets sized as small as a picolitre is deposited from the nozzle of a specialized printer onto the desired position on the flexible substrate [60]. After the deposition, the silver layer is thermally cured up to 150C^0 to ensure that the traces are conductive for antenna application. The process flow of this method is summarized in Figure 9. Unfortunately, this is a costly technique due to the challenges of implementing highly conductive traces, besides the required high post-curing temperatures [59]. An example of this method is the use of silver nanoparticle ink to print a flexible multiband antenna designed on a flexible Kapton substrate (ε_r = 3.5, tan δ =0.002) using the generalized iterative method. The printing is performed using a specialized DMP 2831 printer(Figure 10(a)) [61].

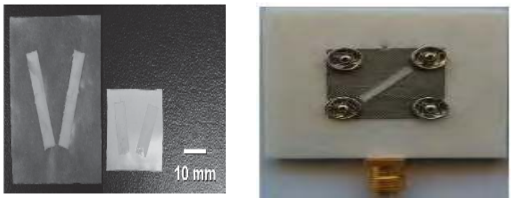
Meanwhile, in [62], a patch antenna was printed on a polyester cotton fabric to operate in the industrial, scientific and medical (ISM) band (2.45 GHz) using the same industrial printer. An interface layer using polyurethane-based paste is used to avoid direct printing onto the cotton substrate with high surface roughness. Since the paste is UV-treatable, damage to the substrate is minimized. To prevent the post-heating process during inkjet printing, a simultaneous sintering and deposition system has been introduced in [63].

Its complete process is illustrated in Figure 10. Here, silver ink is deposited onto flexible substrates (such as PAN, PET, Basat) placed on a preheated plate at 130C^0, eliminating the need of a separate post-heating process in the oven.

Innovations in this fabrication process have resulted in the introduction of water-soluble silver ink, which was successfully printed on different flexible substrates [63]. The electroconductive layer was printed using a digital printer onto different textile substrates such as cotton, cotton/PET, and aramid, and has resulted in reasonably low surface resistance (of less than 0.49Ω/square), even after several bending cycles. Besides that, a wearable tracking device with an integrated antenna on cotton and polyester substrates have been proposed [32]. Besides that, the highly precise Dimatix printer has been used to print the textronic system on both substrates upon application of the dielectric interface layer in [32]. This is to avoid ink smearing onto the fabric substrate.

To reduce the equipment cost and eliminate the post-treatment of the printed layer, the invention of instant chemically-cured conductive inks has reformed the inkjet printing technology [64]. This relatively new method utilizes an office inkjet printer to deposit a printed conductive layer made from silver nanoparticle (AgNP) without any need for post-processing. Chemical curing of the AgNP ink after the printed antenna fabrication requires special treatment of the substrate surface so that nanoparticles(NPs) could instantly form the conduction paths at room temperature [65]. Meanwhile, in [66], this printing method is implemented for fabricating wearable antennas. A Z-shape antenna has been printed for operation in the ISM band (2.45 GHz) on a low-cost pre-treated PET substrate. Surface morphological measurements have been performed to study the effectiveness of this inexpensive inkjet printing technique. Moreover, its surface roughness has also been measured using a 3D surface profiler, and its AC resistance losses have been calculated to show its viability for antenna applications.

The fabrication of wearable antennas is challenging and requires low-cost prototyping, the accuracy of antenna textures, ease of mass production and more importantly, integration with the wearers' outfits. To support the realization of wearable antennas, several techniques have been proposed. The SIW method improves isolation between the antenna and the wearers' body but suffers from complex fabrication processes. Meanwhile, the embroidered antenna is suitable for seamless integration of antenna with garments but suffers from low conductivity for antenna applications. Next, screen printing is lower in cost and environmentally friendly.



(a) (b)

FIGURE 11. Various miniaturization techniques for wearable antenna using (a) high dielectric nanopaper [71], (b) Slotted patch [73].

However, this technique lacks control of the conductor thickness, besides poor printing resolution.

IV. MINIATURIZATION TECHNIQUES FOR WEARABLE ANTENNAS

Miniaturization techniques will enable the more effective use of wearable antennas operating in the lower frequencies such as in the VHF and UHF bands. These licensed bands are widely being used for the land mobile radios, which is a critical communication means for emergency responders. Moreover, miniaturization techniques can beneficial for the implementation of performance-enhancing elements potentially useful for wearable antennas such as frequency selective surfaces, superstrates or backings. These methods ensure that the overall antenna structure should have the smallest possible thickness, with minimized lateral size due to the scarcity of space on the body and for comfort reasons [67].

The first miniaturization technique is the Substrate Integrated Waveguide (SIW) antennas and metasurface based antennas. Despite being electrically small, they are complex in unit cells, which limits their applications [68], [69]. On the other hand, the work in [70] introduced shorting pins in flexible substrates to enable the design of miniaturized WBAN antennas. However, the degradation in terms of radiation efficiency due to the human body is not studied.

Next, nanocomposite paper substrate with high dielectric value (*k*) was used to miniaturize a dipole antenna working at 2.4 GHz [71] (Figure 11(a)). The combination of high-*k* silver nanowire/nanopaper substrate successfully reduced the dipole size by about 50% compared to ordinary nanopaper antenna designed for operation at 2.4 GHz with low radiation efficiency. Besides planar radiating structures, miniaturized button antennas for wearable applications have been proposed [72]– [74]. Substrates such as the transparent acrylic fabric sheet, and Cuming foam (PF-4) have been used with snap-on (SO) buttons and implemented in daily outfits. Recently, the High Impedance Surface (HIS) has been proposed to miniaturize an antenna for use in a smart wristwatch application [75]. This design resulted in a peak directivity of 6.3 dBi. Another miniaturization technique is the Electromagnetic Bandgap Structure (EBG), which is validated to be capable of minimizing to the size of a circular textile antenna in self-monitoring wearable devices [76]. Besides antenna miniaturization, the generation of surface waves was also enabled using the EBG structure, which was implemented

TABLE 4. Flexible single/dual polarized wearable antennas.

Ref.	Technique	application	Drawback
[81]	corner-fed and shorting pins	Wristwatch	LP signal reception
[36]	Meander line parasitic elements	on-body signal reception	End fire radiation direction.
[82]	Truncated patch with shorted pins	soldier berets	Shorted pins with coaxial feeding
[83]	Four sectoral patches along with lumped elements	Smart garment	Coaxial feeding with lumped elements
[80]	CSRR on patch	implantable	coaxial feeding with low gain

using a Shieldex conductive metalized fabric and conductive threads. Another work designed a Complemented Split Ring Resonator (CSRR) to miniaturize patch antennas [77], [78]. Slits in the concentric slots in the CSRR contributed to the compact antenna structure, with a slight decrease in overall gain.

In summary, the miniaturization of the wearable antenna will address the shortage of space and the possible structural deformation when worn on various curvatures of the wearers' body. The main challenge is to ensure wearable antennas feature low-profile, lightweight and compact with high radiation efficiency. This consequently leads to seamless integration into the wireless wearable system. The compact wearable antenna should be safe and can minimize the effects of proximity to the human body. Moreover, the wearable antenna should possess large bandwidth with appropriate polarization robustness which will then enable the compensation of the detuning, while maintaining the compactness of wearable antenna.s

V. WEARABLE SINGLE AND DUAL POLARIZED ANTENNAS

Wearable devices being potentially the most effective outdoor location tracking system, the design of circularly-polarized wearable antennas which can function with least disruptions to their operation, given the dynamics of the human body, will enable its effective implementation. The requirement is even more challenging with the use of the more accurate Global Navigation Satellite System (GNSS), which requires the antenna to be circularly polarized and broadband to support the multiple satellite constellations.

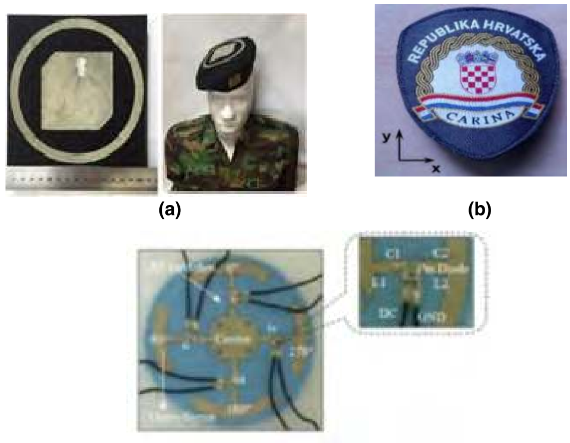
GNSS-enabled devices are typically used in surveying, vehicle navigation or tracking, rescue operations or tracking of military personnel, and health and activity monitoring systems. Most of these units are integrated into cellular telephones, tablet computers, cameras, and wearable outfits, and watches [82]. Generally, GNSS devices require their receiving antenna to be circularly polarized (CP) to improve polarization mismatch during operation and also to provide inherent immunity towards time-varying orientations between transmitter and receiver in an off-body wearable application. Most importantly, the ability for an antenna to be operated in the GNSS L1/E1 band with circular polarization is a key feature for outdoor wearable applications. The following sections will first present the typical circular polarization generation techniques used in wearable antennas, followed by available literature on these antennas designed for single/dual band applications.

A simple and unobtrusive diagonally fed patch antenna fabricated using commercial textiles to be integrated into a sleeve badge for security personals has been proposed in [83]. The antenna showed wide fractional bandwidth (5.6%) with right-handed circular polarization (RHCP) gain of 4.7dBi suitable for the wearable application. The corner truncated patch slot was used to generate the required phase shift in the current distribution to achieve CP.

CSRR (Complementary Split Ring Resonator), a popular type of resonator unit cell, was also proven to be capable of enabling multiband operation [84], miniaturization [85], and CP generation for a patch antenna [78]. In [78], CP is generated by controlling the slit size of the CSRR, ensuring a compact size at the cost of a −17 dBi realized a gain while being on wearers body. This structure, however, is designed for implantable applications and is non-planar. Moreover, it is fed using a probe-feeding technique, which is again, unsuitable for wearable applications. There is limited available literature on compact CP wearable antennas for location tracking application. Note that an antenna with a large ground plane size potentially suffers from operation frequency shift due to bending effects. To overcome this issue, the flexible printed antenna used a meandered ground plane for miniaturization and to enable operation in the GPS band [36].

The realized gain of the antenna is reported to be 3.5 dBi with Front to Back Ratio (FBR) of 13.44dB. Despite this, no SAR evaluation was provided. Despite being linearly polarized, a loop antenna was introduced to be integrated into the lower metal frame of a wristwatch for GPS signal reception in [79]. A gain of 3.2 dBi is observed when the smartwatch was assessed in the presence of a human arm.

Due to the evolution of wearable devices such as activity trackers, pet fits, smart watches and pedometers, there is a growing need for integrated wearable antennas exhibiting multi-band operation to accommodate multiple services in a single device with required polarization [7]. An example is an all-textile wearable antenna using conductive fiber implemented on a felt substrate, integrated with shorted pins proposed for indoor/outdoor positioning systems [80], as seen in Figure 12(a). Two separate ports, as shown in Figure 12(c), were used to excite the antenna for circular polarization (CP) and linear polarization (LP) radiations at the same time. Next, lumped components have also been integrated into textile materials for a rescue and tracking system in [81]. RF switches were implemented to enable dual-polarized characteristics on the probe-fed GPS antenna, which is designed to be part of jackets and raincoats. A three-dimensional LP antenna structure working on both GPS/WLAN bands 9 for wrist-worn application [86]. This dual band and the dual-feed antenna evaluated on human hand-phantom exhibited reasonable radiation performance in term of its gain and efficiency.



(c)

FIGURE 12. Single/dual polarized wearable antenna: (a) Truncated patch [80], (b) Diagonally fed patch [83], (c) textile antenna with lumped elements [81].

VI. EFFECTS OF THE HUMAN BODY ON WEARABLE ANTENNAS

It is well known that antenna reflection and radiation characteristics tend to change due to the interaction with the lossy human body tissues. Moreover, the permittivity of human tissues vary with its type (skin, fat, muscle, etc) and its operating frequency. These distinct permittivity and conductivity values mainly influence the reflection coefficients, affect the power absorbed by the body, and hence decreasing the radiation efficiency of the antenna. For instance, it was observed that that there is an increased radiation loss when an antenna is operated on the chest ($\varepsilon_r = 53.08$, $\sigma = 3.458$ S/m) in comparison to when placed on the upper arm ($\varepsilon_r = 5.3$, $\sigma = 0.095$ S/m) at 2.45 GHz [87]. Moreover, the average human body consists of 65 to 80 % of water content ($\varepsilon_r = 75$ at 25 C^0), which obviously increases the dielectric loading on the antenna. This increase in effective permittivity of the body-worn antenna due to its proximity to the body lowers the Q factor of the antenna. In addition, the flux of the antenna in the vicinity of the human tissues compresses, and the antenna appears to be electrically larger and radiates at lower frequencies compared to free space. Hence, dielectric loading on the antenna can adversely affect its radiation efficiency, gain, radiation pattern, and E-field distribution, drastically reducing its overall performance.

Despite being able to control or cure diseases such as cancer [88], ionizing radiation may increase body temperature. On the other hand, despite the fewer concerns due to non-ionizing EM radiation, electromagnetic absorption for wearable devices including antennas are regulated by the Specific Absorption Rate (SAR) limits. SAR quantifies the amount of EM radiation a human body can withstand without

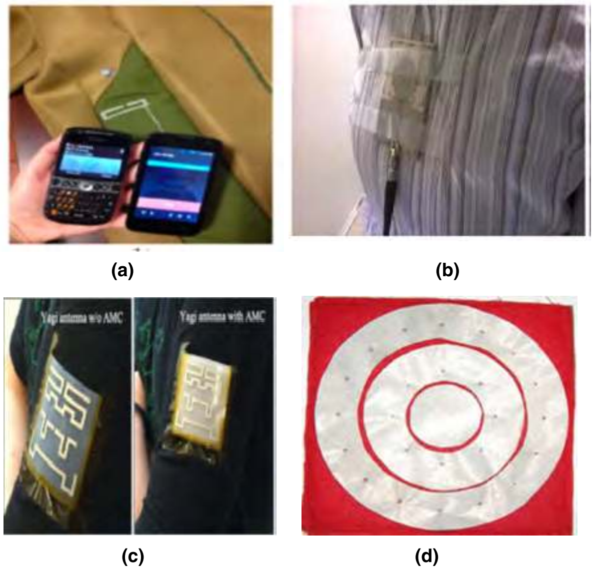


FIGURE 13. (a)Antenna integrated in smart E-coat [96], (b)On-body measurements of All-textile antenna [97], (c) AMC backed Yagi antenna on non-woven latex substrate [98], (d) Soft surface on felt [94].

any health hazards and is defined as the ratio between the transferred power and the mass (kg/lb) of the body where the values are being evaluated [89], [90]. Therefore, one of the main concerns on the use of wearable antennas is strategies taken to limit its SAR in compliance with international standards.

Various planar structures consisting of large ground planes [91], ferrite-based substrates [92], thin mesh-wire planes [93], soft surfaces [94], thick fabric Layers [95], and AMC metasurfaces [99] have been proposed to isolate the antenna from the potential effects of the host body. As reported in [97], a multi-layered, all textile antenna has been fabricated with a full ground plane to attain unidirectional radiation pattern and low SAR value for on-body communication (see Figure 13(b)). The design exploited multilayered planar antenna topology with a full ground plane on its rear to attain high fidelity with wide bandwidth. This resulted in reduced back radiations for wearable UWB impulse radio communications. The lowest SAR value of 0.52 W/kg was reported at 7 GHz for this antenna without using any additional layers.

The concept of a reflector plane based on the AMC can also be used to improve the performance of wearable antennas when operating on body. In [100], a hexagonal dual band AMC using copper tape on felt and denim substrate has been used to increase the gain of the patch antenna. AMC such as the slotted Jerusalem Cross (JC) ground plane was also proposed to reduce the effects of back radiation of the antenna on the human body [101]. The use of the miniaturized slotted structures in the AMC decreased SAR by up to 64% while improving the gain up to 3.7 dBi in comparison to the standalone antenna. In [96], a dual band all textile antenna has been proposed for a smart coat (*E*-Caption) using Cordura substrate was proposed, as shown in Figure 13(a). This dual band patch antenna has been fully integrated into the coat material by using a lamination technique without using steam. Morphological analysis has been performed to ascertain the effectiveness of this lamination method, which proved the electrical surface resistance of the patch and the relative permittivity of the substrate are not significantly changed. Besides that, an omnidirectional radiation pattern and reasonable gain of 3.3 dBi was achieved while being worn by a volunteer.

In [75], an Inverted-F Antenna using optimized High Impedance Surfaces (HIS) was also proven to reduce the human body effects on the radiation efficiency substantially. The integration of an array of 2 x 2 unit cells improved the overall gain of the antenna to 6.9 dBi, with more than 90 % of SAR reduction. This made the antenna very attractive for a wrist watch wearable application with a radiation efficiency of 48 % when worn on the human wrist. Besides that, SAR has also been evaluated when the antenna is operated in bent conditions. This was performed on a dual band textile antenna operating in both ISM bands (2.4GHz and 5.8GHz). A reduced SAR value of 0.054 W/kg was obtained when the antenna was being bent along the *y*-axis using a curvature of radius 60 mm [102]. Next, a dual band AMC structure on a dual-layered non-woven substrate was printed using silver ink for wearable applications [98]. Meanwhile, the heat effects of the antenna radiation on the human biological tissues were discussed in [103] by investigating a patch antenna operating on the body. Different back radiation reduction techniques are compared in Table 5 for better illustration.

Studying different isolation techniques in wearable antenna designs is crucial. This will ensure the safety limits of electromagnetic absorption imposed by regulatory agencies to ensure the well-being of the wearers. Moreover, adding structures for isolation typically result in a bulky and lossy antenna in nature. Hence, there is a need for these techniques to be employed which ensures the compact size of the wearable antenna, while maintaining the required operational parameters and providing enough isolation from the body to comply with SAR standards. Next, the placement location of the antenna on the body is also essential. For instance, a wearable antenna may suffer more frequency drift, gain, and radiation pattern distortion when placed on the chest due to high dielectric constant values of the muscles as compared to other parts of the body.

VII. EFFECTS OF BENDING ON WEARABLE ANTENNAS

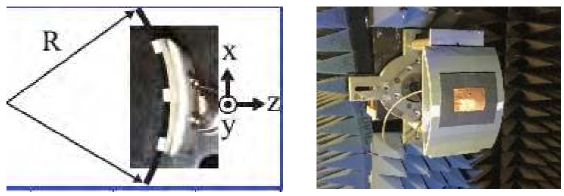
As wearable antennas are mostly worn by human or living beings, mechanical deformation such as bending are unavoidable when implemented using textiles or flexible materials. It is well known that bending the antenna in some particular direction degrades its performance for the intended application [107]. This is not limited in terms of shifting their resonant frequency, but also affects antenna polarization, especially, when circular polarization is required [108].

TABLE 5. Review of back radiation mitigation techniques for wearable antennas.

Ref	Antenna structure	Mitigation techniques (SAR W/kg over 10g)	Material and Fabrication Technique	Application	Disadvantage
[99]	Truncated patch	Full-ground reflector plane (0.52)	Manual cutting: Felt substrate	On-body devices (2-10.6 GHz)	radiation efficiency is not provided.
[98]	Monopole antenna	The coating material is used (N.A.)	laser cutting machine: adhesive sheet on Zelt fiber	Energy harvesting application: GSM and DCS bands.	Moistening effect in the textile fabric is not provided
[77]	Inverted L antenna	HIS (0.29)	Wet etching using FR4 substrate	Wristwatch (2.4 GHz)	Radiation eff. is only 48%
[93]	Wire antenna	The ground plane on the eye frame. (0.85)	Etching on the PCB	Eyeglasses for 4 G application.	The rigid substrate with copper.
[95]	Monopole antenna	Thin wire mesh sheet. (N.A.)	PCB etching	802.11 ac application	Fabrication complexity
[71]	Broadband Monopole	Metallic I-shape metasurface(0.66)	Inkjet printing	Wearable application	Costly printer and AgNP ink used
[106]	Meander line antenna	The parasitic element is used.(N.A.)	Simple adhesive aluminum sheet	Sensor wearable nodes	Susceptible to bending cycles
[96]	Circular patch antenna	Soft surfaces(N.A)	Textile fabrication	Wearable application	Cracks after many bending cycles
[107]	Unilateral CPW Patch	Asymmetric radiating patch (N.A.)	FR4	Mobile phone	No flexibility.
[94]	patch	Using ferrite sheet to the antenna(0.026)	FR4	Mobile phone	Rigid and expensive material
[108]	Fractal-based monopole patch	EGB is used for SAR reduction(0.024)	Textile	wearable	Cracks after many bending cycles

One of the techniques to alleviate these effects and maintain antenna performance during bending or crumpling is to ensure a wideband operation. This is so that their resonant frequency could be kept within the required operating region even after bending [109]. Secondly, wearable antennas can be designed to be as symmetric as possible so that they are affected minimally despite being bent in different directions. In [70], the authors fabricated three different types of textile antennas using Copper Foil Tape (CFT) and Shieldit (SH) on a felt substrate. Shorting pins between the patch and ground plane were attributed to the minimal bending and crumpling effects on the antenna performances at the cost of fabrication complexity.

AMC structures are proved to be less susceptible to mechanical deformation for wearable applications. This has been found from the various AMC backed wearable antennas investigated under different bending conditions [67], [110]– [112]. For instance, a wideband antenna with a full ground plane backed by AMC array was reported in [112]. The first wideband antenna is designed and verified under different bending conditions, prior to the employment of the AMC plane to increase its gain and FBR. Next, in [69], the efficiency of a monopole antenna was reported to be slightly reduced by using the patch antenna with metallic backed anisotropic I-shaped metasurfaces. It was also proven that the effects of bending and the existence of the human body in its proximity could be mitigated using the metasurface. Meanwhile, a dual band fractal based monopole antenna was proposed in [106]. It is fabricated on a jeans fabric, and its effects were investigated regarding bending and crumpling to demonstrate the effectiveness of the EBG structure for wearable applications [113].



(a) (b)

FIGURE 14. Bending of (a) Snap-On button [73], (b) patch on 3-D printed bended bracket [114].

Bending and crumpling effect on the wearable antenna has also been investigated in [115]. This study was performed on a textile antenna backed by EBG, which indicated bandwidth degradation and shifting of resonance due to bending. Besides that, bending of the antenna in any of the major plane resulted in an increase of beam width with a decrease in the overall gain.

For wearable CP antennas, bending affects their radiation performance, as expected. Bending not only changes their resonant frequency for such CP antennas but also degrades its polarization properties [108]. On the contrary, bending affects the resonant frequency of linearly-polarized antennas due to changes in its effective length. Besides planar antennas, bending effects on the resonant frequency and AR characteristics were studied for a Snap-On button antenna in [73] (Figure 14(a)). Substrates such as the transparent acrylic fabric sheet, and Cuming foam (PF-4) have been used with snap-on (SO) buttons and implemented in daily outfits. The antenna is reported to be working effectively even after being tilting along the y-axis with a radius of 30 mm. However, bending along the x-axis should be avoided due to the abrupt change in the effective length of the antenna, resulting in severe degradation in the radiation performance. The deterioration in AR was also reported in [116]. Wearable antennas working in GPS/WLAN bands have also been investigated under different bending conditions for a military beret in [80]. It is shown that the axial ratio and reflection coefficient behavior remain within the required limits for the case of the beret. This is found when studying the antenna when bent over a cylinder with a radius of 180 mm, considering the maximum bending for an antenna placed on a human head.

Physical deformation is one of the main concern in ensuring the effective operation of wearable antennas. Besides shifting the resonant frequency of the wearable antennas, it also affects its polarization due to change in the current density on the radiating elements. Moreover, this also potentially increases the SAR values on the wearer's body. To design a wearable antenna, it is imperative to devise some methods to eliminate these effects. In addition, one should try to place an antenna in such a way that it should not be bent along the y-axis as it will cause more severe performance degradation. Next, the antenna can be made as small as possible to avoid the significant change in the effective length of the antenna during bending.

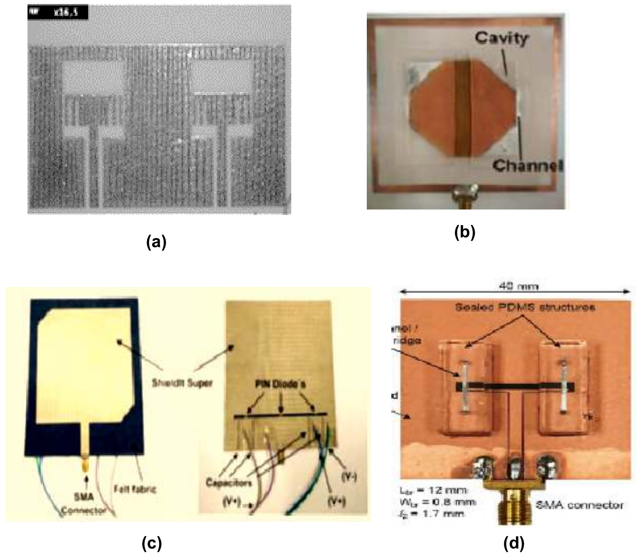


FIGURE 15. Frequency reconfigurable wearable antennas (a) inkjet printed antenna [121], (b) metal filled patch [128], (c)slotted textile antenna [123], and (d) liquid filed slot antenna [126].

VIII. RECONFIGURABLE WEARABLE ANTENNAS

It is also expected that the planar orientation of the antenna when placed on the body, although mechanically acceptable, may actually limit their capability in terms of direction of radiation. This is especially evident considering that a wearable node at a specific on body location may need to communicate with other on-body nodes (at the end-fire direction), and alternately, need to channel sensed/aggregated data to a base station located off-body (at the broadside direction), or even to collect data from an in-body implant. This requires the wearable antennas to be ideally switchable. The reconfigurable(switchable) multiband wearable antenna has gained much attention as they merge numerous devices from healthcare to entertainment working on various standards and applications into a single radiating platform.

Different types of surface-mounted switches such as positive-intrinsic-negative (PIN) diodes, field effect transistor (FET), inductors and varactor diodes are being used to enable frequency reconfigurability [117]– [119]. One of these examples is, where a compact and flexible reconfigurable antenna inkjet printed on PET substrate in [111]. PIN diode mounted on the edge of the T-slot patch enabled frequency and polarization reconfigurability for WiMAX and WLAN applications in a wearable form. Next, a dual-band AMC plane has been placed under this T-shaped slot antenna to enhance its radiation performance, with a reduction in SAR values both in bent and flat configurations [110]. Both the abovementioned structures do not require any biasing circuits, via holes or shorting pins to activate the PIN diodes. To fabricate lightweight, low cost, and conformal wearable antenna, the researchers in [120] used a photo paper substrate to print a low cost reconfigurable antenna operating in various bands from 1.5 to 5 GHz for conformal applications. The proposed design employed only two PIN diodes to redirect the current paths towards multiple radiators on a paper substrate. The antenna achieved a maximum realized gain of 2 dBi with 50 % of radiation efficiency. In [121], as shown in Figure 15(a), symmetrical slots on a patch radiator terminated with a pair of switches have been proposed to enable reconfiguration between two prospective 5G frequency bands (28 and 38 GHz) on a flexible substrate. The antenna channel capacity is further enhanced by the introduction of a two-element multiple-input and multiple -output (MIMO) antenna system on the same substrate. This is implemented using an inkjet printing method on a chemically-cured PET substrate to enable a fully bendable and flexible antenna system for wearable applications.

Due to excellent thermal conductivity and mechanical strength, graphene ink has also been used to print a wearable satellite broadcast reception system [122]. A multilayered textile substrate has been used to overcome poor electric conductivity of the printed patch antenna. The antenna gain is improved by 4.9 dBi using only two external RF switches and employing a multi-mode propagation technique. Besides that, a frequency reconfigurable textile antenna on Felt substrate using Shieldex fabric has been proposed in [123]. The antenna, shown in Figure 15(c), operates from 1.54 GHz to 2.82 GHz. Tuning for this corner-truncated CP patch antenna is facilitated by changing the slot length on the ground plane using three embedded RF switches.

Besides that, flexible substrates filled with liquid metals are also gaining attention among researchers for tuning multi-band antennas [124]. Liquid metals not only can provide reconfigurability but also contributes to miniaturization of the antenna as first proposed in [125]. An excellent example of compact and tunable antennas is proposed in [126]. Two microchannels filled with Galinstan have been designed to enable a high-strength electric field between the Galinstan bridges and the CPW slot antenna, as illustrated in Figure 15(d). This results in reactive loading of the antenna which shifts the operating frequency downwards. The Galinstan bridges are fabricated using PDMS and channels are sealed entirely afterward to achieve a compact CPW folded slot antenna with a miniaturization factor of 85 %. The similar liquid has been filled in PMMA channels fabricated using a 3D printer and exhibits tunability within the frequency range from 14.2 to 15.1 GHz in [127]. More recently, as shown in Figure 15(b), a polarization reconfigurable aperture-coupled patch antenna by filling metal alloy (EGaIn) in four different cavities enclosed using silicon rubber (Ecoflex) and PET film has been proposed in [128]. Here, the location of the pressure-driven liquid metal enabled different polarization states such as LP, RHCP, left-handed circular polarization (LHCP) for the antenna. High radiation efficiency is observed due to minimal usage of liquid and silicon rubber.

The reconfigurable feature in wearable antennas provides for its ability to combat fading losses, mitigate the channel interference, and tackle polarization variations. The main challenge is to provide reconfigurability with minimal circuitry, without biasing circuits, and more important it should have less detuning effects being near to the human body. It is also such this reconfigurable feature will also be attractive as soon as millimeter-wave systems are being implemented as in the form of wearable devices.

IX. ENERGY-HARVESTING WEARABLE RECTENNAS

Finally, as with any portable devices, wearable nodes are ideally required to be autonomous – they are expected to have enough resources (in terms of processing power and energy) to perform their tasks for the longest possible duration independently. One of the most effective methods to ensure energy sustainability for wearable devices is to ideally integrate energy harvesting components into them. The wearable antennas in these devices can be deemed the most suitable due to its relatively large unobstructed space available for the integration of RF- or even solar energy harvesting components.

The primary motivation behind battery and maintenance free wearables is the availability of energy harvesting (EH) via wireless technologies, the development of low-power electronics, the need for sustainable power sources and a quest for autonomous lifestyle [129]. Omnipresent RF energy at different frequency bands can be harvested to realize these type of battery-independent wearable devices [130]. An example of such devices is the multilayered structure with a slotted annular-ring patch on a low-loss pile substrate backed by full ground plane [131]. This structure has been proposed to scavenge RF energy from the prevalent GSM (900 MHz and 1.8 GHz) and WLAN (2.45 GHz) bands.

To achieve maximum power conversion, a single-stage power converter has been integrated with a broadband phase shifter to realize this CP rectenna for polarization and orientation independent RF energy reception from all directions. Meanwhile, a conformal hybrid system combining solar cell and EM energy harvester has been proposed in [132]. A broadband monopole antenna was first fabricated on a PET substrate, followed by the mounting of a silicon-based solar cell onto the monopole for space efficiency. The system exhibited an overall energy harvesting system efficiency with an irradiance value of 99 mW/cm^2 in an open-air environment. Next, a CPW flexible antenna with an EH module is integrated with a separate booster circuit to counter the lower (AC to DC) conversion efficiency was proposed in [133]. The proposed slotted patch antenna is designed on a flexible substrate (εr =10.2, tan δ = 0.0023) with compact booster circuit on its reverse side. The measured power efficiency of 44 % made this flexible EM rectenna system suitable for the wearable application. Next, a fully-textile wearable rectenna system operating in the UHF band is introduced in [134]. The rectenna implemented with a full-bridge rectifier is made using textile materials and exhibited more than 20% conversion efficiency in the UHF band. The patch is fabricated using fray-less nonwoven conductive textiles and designed on a bi-layered textile substrate made of pile and jeans. The rectifier circuit is attached to the ground plane on the jeans substrate and completes this all-textile wearable rectenna structure. Besides that, a wearable ambient RF energy harvester on a biodegradable paper substrate to realize low-cost, ultra-lightweight, conformal battery-less rectenna is proposed in [135]. The paper-based rectenna system exhibited a maximum 57% of conversion efficiency, with the compact size of 11 × 11 mm^2, see Figure 16(c). Meanwhile, another flexible antenna for wristband application has been proposed in [136]. A rectifier is connected to the textile antenna through a coupled microstrip line. Such setup featured a conversion efficiency of 33.6 % at −20 dBm. The proposed system can be worn on the wrist and have minimal human body effect due to a full ground plane (Figure 16(d)).

Energy harvesting is one of the most desirable solutions in ensuring power autonomy, and maintenance-free battery in wearable devices. The challenging tasks in realizing a complete wearable rectenna are the reliability of interconnections between flexible and rigid subsystems, maximizing power conversion efficiency to increase transfer range, and the maintenance of efficiency and radiation pattern on the human body. To address this, several technology enablers have proposed system setups aimed at extracting energy from diverse sources within the wearers surrounding environment, including light, EM radiation, and thermal body energy or motion from the wearer's body.

X. UNIQUE WEARABLE ANTENNA TECHNIQUES

There are many situations when a wearable antenna has to be mounted on specific locations or part of the clothing for unobtrusive effective on/off body communications. One of

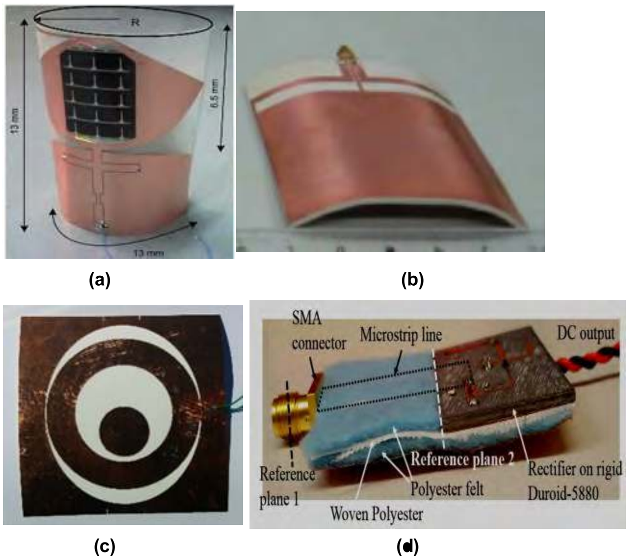


FIGURE 16. Wearable rectenna systems (a) Solar cell rectenna [132], (b) rectenna with booster circuit [133], (c) Paper based rectenna system [135], and (d) wrist band RF harvester [136].

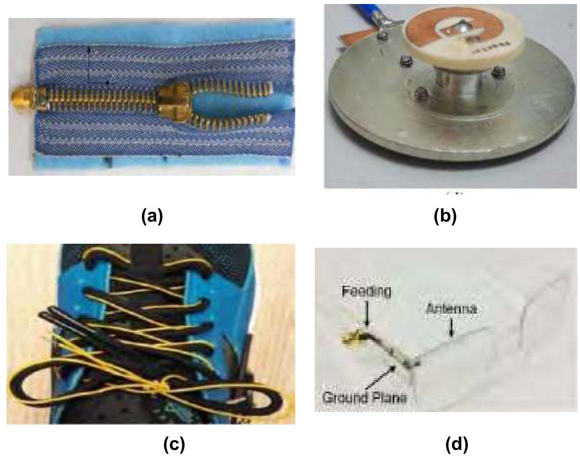


FIGURE 17. (a) Button antenna [138], (b) Zip antenna [139], (c)Shoelace antenna [142], and (d) Glasses antenna [147].

these examples is to button the antenna on the shirt/coat of the wearer outfits. This not only saves the antenna from the risks of degradation due to their physical deformation, but also enables performance stability of these antennas due to its rigid substrate. Besides that, such method also provides an alternative attachment method to clothes instead of the traditional sewing or printing methods. Moreover, button antenna can be easily integrated using copper as its conductive material, which is likely to outperform other more lossy conductive flexible materials in wearables. In [137], the authors proposed a button antenna for on/off body communication and studied its effects for different bending conditions. The reported high efficiency (of more than 90 %) outperforms the other textile antennas for the same applications. Next, a dual-band and dual-polarized button antenna has been proposed for wearable body-centric communication in [138] (Figure 17(a)). Measured efficiencies of 46.3 % and 69.3 % are observed in the upper and lower WLAN band, respectively, when the antenna is evaluated when placed over a human phantom. Moreover, its compact size and reasonable realized gain makes it suitable for use in both on-body and off-body communications. Besides that, the authors in [139] have proposed a new technique by combining inkjet and 3D printing method for RFID applications. This enabled a seamless integration of RFID tag into smart clothes for authentication and access control from the wearer's body, as illustrated in Figure 17(b).

Besides buttons, zippers are also commonly integrated on clothes and other accessories such as bags. They are effective radiators due to their metallic structure and are fairly large. This enables simple, low cost and even tunable antennas to be realized via this method, due to their varying lengths. An instance of the use of this property daily outfits for WLAN communication are demonstrated in [140], [141]. The authors in [141] have integrated monopole antenna in the zip of a hand bag and managed to obtain up to 5 dBi of realized gain at 2.45 GHz. The reported antenna also showed reasonable performance even in the presence of a hand phantom. On the other hand, a zipper antenna sewed onto a pure jeans substrate produced a measured realized gain of 0 dBi in [140].

Next, a shoelace antenna fabricated using a thin flexible wire has been proposed for collision avoidance of the blind [142], as depicted in Figure 17(c). The shoelace has been fed from the bottom of the laces and exhibited an acceptable performance even when being tightened or loosened. In the same way, a new technique by using the strap of a watch as the radiator has been proposed in [143]–[145]. A detailed study of the slotted-metallic strip and its effect on radiation patterns, feeding locations on the strip as well as the impact of arm and hand for wearable WLAN application has been performed [144]. Similarly, the metallic backing of a wristwatch in the form of a cavity-backed annular slot antenna has been proposed for use at the 2.4 GHz WLAN band. The metallic backing not only reduced back radiations but also enhanced the radiation efficiency up to 66 % when assessed on a hand phantom [145]. To increase the transmission capacity for a smart watch, a MIMO antenna has been proposed on a plastic wristband strap by using three-dimensional etching process for operation in the 5.2 GHz WLAN band. The proposed antenna attained 97 % of efficiency in free space, which reduced to 55 % when placed on the hand. Next, an axial-mode helical antenna has been designed on a circular ground plane, featuring an end-fire radiation pattern for on-body communication. The finger-worn antenna operated from 25 to 35 GHz exhibited a good circular polarization property, even when being tilted on the wearers fingers [146].

Besides watches, there are several other wearable antennas which have been designed on glasses. They are intended for ubiquitous wearable applications in implementing augmented reality applications. An instance is in [147], where a transparent antenna located directly on the glasses, near to eyes of glaucoma patients is proposed to measure their intraocular pressure, as shown in Figure 17(d).

The antenna uses multilayered indium–zinc–tin oxide (IAI) film with a conductivity 2×10^6 S/m, resulting in a maximum efficiency of 46.3 % when assessed on a human phantom. Meanwhile, to enable multi-device communication, a dual-band antenna fabricated using the 3D printing technology is implemented on the plastic eye frame for operation in the 2.45 GHz band [148]. The antenna offers pattern diversity to communicate simultaneously with WLAN access points, smartphones, and laptops. It achieved radiation efficiency up to 22.8 % when evaluated on a head phantom. Next, an antenna patch-array have been proposed for wearable application in the 60 GHz band [149]. This antenna array, designed on the ultra-thin Taconic substrate exhibits a directional radiation pattern to achieve a maximum gain of 14.8 dBi in the broadside direction. Besides that, its beam can be steered using appropriate phase excitation at each port to adapt to the time-varying position of the wearers. These are several examples of the interesting recent advancements in the field of the wearable antennas, which is intended for the 5G and future 6G era.

XI. SUMMARY

Wearable antennas are one of the critical components in the realization of wearable and portable devices. Due to their lightweight, flexibility, low cost and conformal characteristics, they are ideal for wireless communication and sensing applications in a worn form. This review first starts with the presentation of applications where wearable devices are found to be most advantageous. Next, the types of flexible materials used and state-of-the-art technologies to realize these structures are explained. The choice of the material types can be made based on considerations such as the application (indoors or outdoors), frequency and accuracy of the smallest dimension, seamless integration into wearers outfits, robustness to harsh weather, and finally, cost and speed of the fabrication. Since antenna needs low-loss dielectric material and highly conductive materials for efficient EM radiation reception/transmission, highly conductive materials such as copper, conductive fabric, metallic inks, conductive polymers and polydimethylsiloxane (PDMS) embedded conductive fiber are new variants used as the conductive parts of wearable antennas. On the other hand, substrate materials such as flexible polymer Kapton, PET, PEN, PANI, liquid crystal polymer, organic material, ferrite magnetic materials, fabric, and paper are good solutions as substrates, owing to their flexible features.

This is followed by the important design and operational issues - back radiation mitigation, miniaturization methods, circular polarization generation techniques, compliance to regulatory EM absorption limits, operation robustness in extreme outdoor environments, alleviation of body effects, and susceptibility to structure deformations. Despite slight variations in severity according to applications, most of these issues exist in the context of body-worn implementation. It is observed from the review that the most important aspect in the design is to minimize coupling to the body, prior to the addition of other features onto the antenna structure. This is aimed at ensuring a robust operation of the antenna on the body first, followed by other enhancements such as miniaturization and bandwidth broadening. Besides that, this will also enable the antenna to be operating in its highest possible efficiency, depending on the type of antenna topology chosen. Several methods in ensuring minimum degradation when working in proximity to the human body have been proposed. They include the use of large ground planes, ferrite-based substrates, thin mesh-wire planes, and metamaterial surfaces.

Finally, the latest researches for two relatively attractive features for wearable antennas are reviewed – reconfigurability and power sustainability via energy harvesting. Despite rendering the design of these antennas even more challenging with such additional features, these features are foreseen to provide wearable antennas with the much-needed autonomy as part of a wearable device. Besides that, their reconfigurability, either in terms of frequency, radiation direction or polarization will enable their continued relevance with the progression of wireless communication towards the 5G and 6G eras.

REFERENCES

[1] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart. 2016.
[2] B. Campbell, "Keysight technologies: The Internet of Things enabling technologies and solutions for design and test," Keysight Technol., Santa Rosa, CA, USA, Appl. Notes, 2016.
[3] P. Friess, *Internet of Things: Converging Technologies for Smart Environments and Integrated Ecosystems*. Gistrup, Denmark: River Publishers, 2013.
[4] A. Ericsson, "Cellular networks for massive IoT-enabling low power wide area applications," Ericsson, Stockholm, Sweden, Tech. Rep. Uen 284 23-3278, Jan. 2016, pp. 1–13.
[5] *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2014–2019*, CISCO, San Jose, CA, USA, 2015, pp. 1–48.
[6] S. Bhattacharyya, N. Das, D. Bhattacharjee, and A. Mukherjee, *Handbook of Research on Recent Developments in Intelligent Communication Application*. Philadelphia, PA, USA: IGI Global, 2016.
[7] M. Chan, D. Estève, J.-Y. Fourniols, C. Escriba, and E. Campo, "Smart wearable systems: Current status and future challenges," *Artif. Intell. Med.*, vol. 56, no. 3, pp. 137–156, Nov. 2012.
[8] S. Seneviratne *et al.*, "A survey of wearable devices and challenges," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2573–2620, 4th Quart. 2017.
[9] D. H. Werner and Z. H. Jiang, *Electromagnetics of Body Area Networks: Antennas, Propagation, and RF Systems*. Hoboken, NJ, USA: Wiley, 2016.
[10] I. Locher, M. Klemm, T. Kirstein, and G. Trster, "Design and characterization of purely textile patch antennas," *IEEE Trans. Adv. Packag.*, vol. 29, no. 4, pp. 777–788, Nov. 2006.
[11] P. Nepa and H. Rogier, "Wearable antennas for off-body radio links at VHF and UHF bands: Challenges, the state of the art, and future trends below 1 GHz," *IEEE Antennas Propag. Mag.*, vol. 57, no. 5, pp. 30–52, 2015.
[12] R. Balint, N. J. Cassidy, and S. H. Cartmell, "Conductive polymers: Towards a smart biomaterial for tissue engineering," *Acta Biomaterialia*, vol. 10, pp. 2341–2353, Jun. 2014.
[13] R. Salvado, C. Loss, R. Gonçalves, and P. Pinho, "Textile materials for the design of wearable antennas: A survey," *Sensors*, vol. 12, no. 11, pp. 15841–15857, 2012.
[14] L. Corchia, G. Monti, and L. Tarricone, "Wearable antennas: Nontextile versus fully textile solutions," *IEEE Antennas Propag. Mag.*, to be published.

[15] M. Park *et al.*, "Highly stretchable electric circuits from a composite material of silver nanoparticles and elastomeric fibres," *Nature Nanotechnol.*, vol. 7, pp. 803–809, Nov. 2012.
[16] M. A. R. Osman, M. K. A. Rahim, N. A. Samsuri, M. K. Elbasheer, and M. E. Ali, "Textile UWB antenna bending and wet performances," *Int. J. Antennas Propag.*, vol. 2012, Mar. 2012, Art. no. 251682.
[17] Y. Kim *et al.*, "Stretchable nanoparticle conductors with self-organized conductive pathways," *Nature*, vol. 500, pp. 59–63, Aug. 2013.
[18] R. B. V. B. Simorangkir, Y. Yang, K. P. Esselle, and B. A. Zeb, "A method to realize robust flexible electronically tunable antennas using polymer-embedded conductive fabric," *IEEE Trans. Antennas Propag.*, vol. 66, no. 1, pp. 50–58, Jan. 2018.
[19] H. A. E. Elobaid, S. K. A. Rahim, M. Himdi, X. Castel, and M. A. Kasgari, "A transparent and flexible polymer-fabric tissue UWB antenna for future wireless networks," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1333–1336, Dec. 2016.
[20] S. Y. Lee, M. Choo, S. Jung, and W. Hong, "Optically transparent nano-patterned antennas: A review and future directions," *Appl. Sci.*, vol. 8, no. 6, p. 901, 2018.
[21] J.-H. So, J. Thelen, A. Qusba, G. J. Hayes, G. Lazzi, and M. D. Dickey, "Reversibly deformable and mechanically tunable fluidic antennas," *Adv. Funct. Mater.*, vol. 19, pp. 3632–3637, Nov. 2009.
[22] R. A. Liyakath, A. Takshi, and G. Mumcu, "Multilayer stretchable conductors on polymer substrates for conformal and reconfigurable antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, no. , pp. 603–606, 2013.
[23] A. Kumar *et al.*, "A highly deformable conducting traces for printed antennas and interconnects: Silver/fluoropolymer composite amalgamated by triethanolamine," *Flexible Printed Electron.*, vol. 2, no. 4, 2017, Art. no. 045001.
[24] L. Song, A. C. Myers, J. J. Adams, and Y. Zhu, "Stretchable and reversibly deformable radio frequency antennas based on silver nanowires," *ACS Appl. Mater. Interfaces*, vol. 6, no. 6, pp. 4248–4253, 2014.
[25] R. B. V. B. Simorangkir, Y. Yang, R. M. Hashmi, T. Björninen, K. P. Esselle, and L. Ukkonen, "Polydimethylsiloxane-embedded conductive fabric: Characterization and application for realization of robust passive and active flexible wearable antennas," *IEEE Access*, vol. 6, pp. 48102–48112, 2018.
[26] Z. Hamouda, J.-L. Wojkiewicz, A. A. Pud, L. Koné, S. Bergheul, and T. Lasri, "Magnetodielectric nanocomposite polymer-based dual-band flexible antenna for wearable applications," *IEEE Trans. Antennas Propag.*, vol. 66, no. 7, pp. 3271–3277, Jul. 2018.
[27] P. Salonen, Y. Rahmat-Samii, M. Schaffrath, and M. Kivikoski, "Effect of textile materials on wearable antenna performance: A case study of GPS antennas," in *Proc. IEEE Antennas Propag. Soc. Symp.*, vol. 1, Jun. 2004, pp. 459–462.
[28] T. Rai, P. Dantes, B. Bahreyni, and W. S. Kim, "A stretchable RF antenna with silver nanowires," *IEEE Electron Device Lett.*, vol. 34, no. 4, pp. 544–546, Apr. 2013.
[29] G. Xiaohui *et al.*, "Flexible and reversibly deformable radio-frequency antenna based on stretchable SWCNTs/PANI/Lycra conductive fabric," *Smart Mater. Struct.*, vol. 26, no. 10, 2017, Art. no. 105036.
[30] R. Ashayer-Soltani, C. Hunt, and O. Thomas, "Fabrication of highly conductive stretchable textile with silver nanoparticles," *Textile Res. J.*, vol. 86, pp. 1041–1049, Sep. 2015.
[31] S. B. Roshni, M. P. Jayakrishnan, P. Mohanan, and K. P. Surendran, "Design and fabrication of an E-shaped wearable textile antenna on PVB-coated hydrophobic polyester fabric," *Smart Mater. Struct.*, vol. 26, no. 10, 2017, Art. no. 105011.
[32] B. Krykpayev, M. F. Farooqui, R. M. Bilal, M. Vaseem, and A. Shamim, "A wearable tracking device inkjet-printed on textile," *Microelectron. J.*, vol. 65, pp. 40–48, Jul. 2017.
[33] A. Rahman, M. T. Islam, M. J. Singh, and N. Misran, "Sol–gel synthesis of transition-metal doped ferrite compounds with potential flexible, dielectric and electromagnetic properties," *RSC Adv.*, vol. 6, pp. 84562–84572, Aug. 2016.
[34] S. Park *et al.*, "Silicones for stretchable and durable soft devices: Beyond Sylgard-184," *ACS Appl Mater. Interfaces*, vol. 10, pp. 11261–11268, Apr. 2018.
[35] S. D. Nivethika, B. S. Sreeja, E. Manikandan, and S. Radha, "A stretchable smart and highly efficient radio frequency antenna on low cost substrate," *Microw. Opt. Technol. Lett.*, vol. 60, pp. 1798–1803, Jul. 2018.
[36] M.-C. Tang, B. Zhou, and R. W. Ziolkowski, "Flexible uniplanar electrically small directive antenna empowered by a modified CPW-feed," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 914–917, 2015.
[37] H. F. Abutarboush, M. F. Farooqui, and A. Shamim, "Inkjet-printed wide-band antenna on resin-coated paper substrate for curved wireless devices," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 20–23, 2016.
[38] A. Tsolis, W. G. Whittow, A. A. Alexandridis, and J. Vardaxoglou, "Embroidery and related manufacturing techniques for wearable antennas: Challenges and opportunities," *Electronics*, vol. 3, no. 2, pp. 314–338, 2014.
[39] R. Seager *et al.*, "Effect of the fabrication parameters on the performance of embroidered antennas," *IET Microw., Antennas Propag.*, vol. 7, no. 14, pp. 1174–1181, Nov. 2013.
[40] H. Rogier, "Textile antenna systems: Design, fabrication, and characterization," *Handbook of Smart Textiles*. New York, NY, USA: Springer, 2015, pp. 433–458.
[41] N. F. M. Aun, P. J. Soh, A. A. Al-Hadi, M. F. Jamlos, G. A. E. Vandenbosch, and D. Schreurs, "Revolutionizing wearables for 5G: 5G technologies: Recent developments and future perspectives for wearable devices and antennas," *IEEE Microw. Mag.*, vol. 18, no. 3, pp. 108–124, May 2017.
[42] M. Bozzi, A. Georgiadis, and K. Wu, "Review of substrate-integrated waveguide circuits and antennas," *IET Microw., Antennas Propag.*, vol. 5, no. 8, pp. 909–920, 2011.
[43] F. Ghanem, R. Langley, and L. Ford, "Propagation control using SIW technology," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, Jul. 2010, pp. 1–4.
[44] B. Mandal and S. K. Parui, "Wearable tri-band SIW based antenna on leather substrate," *Electron. Lett.*, vol. 51, no. 20, pp. 1563–1564, 2015.
[45] M. E. Lajevardi and M. Kamyab, "A low-cost wideband quasi-yagi SIW-based textile antenna," *Prog. Electromagn. Res. Lett.*, vol. 67, pp. 53–59, Jan. 2017.
[46] M. E. Lajevardi and M. Kamyab, "Ultraminiaturized metamaterial-inspired SIW textile antenna for off-body applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 3155–3158, 2017.
[47] M. Bozzi, S. Moscato, L. Silvestri, N. Delmonte, M. Pasian, and L. Perregrini, "Innovative SIW components on paper, textile, and 3D-printed substrates for the Internet of Things," in *Proc. Asia–Pacific Microw. Conf. (APMC)*, 2015, pp. 1–3.
[48] J. Virkki, Z. Wei, A. Liu, L. Ukkonen, and T. Bjorninen, "Wearable passive e-textile UHF RFID tag based on a slotted patch antenna with sewn ground and microchip interconnections," *Int. J. Antennas Propag.*, vol. 2017, Feb. 2017, Art. no. 3476017.
[49] J. Zhong, A. Kiourti, T. Sebastian, Y. Bayram, and J. L. Volakis, "Conformal load-bearing spiral antenna on conductive textile threads," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 230–233, 2017.
[50] I. Gil, R. Seager, and R. Fernández-García, "Embroidered metamaterial antenna for optimized performance on wearable applications," *Phys. Status Solidi (a)*, vol. 215, no. 21, 2018, Art. no. 1800377.
[51] I. Gil, R. Fernández-García, and J. A. Tornero, "Embroidery manufacturing techniques for textile dipole antenna applied to wireless body area network," *Textile Res. J.*, vol. 89, no. 8, pp. 1573–1581, 2018.
[52] X. Chen, L. Ukkonen, and J. Virkki, "Reliability evaluation of wearable radio frequency identification tags: Design and fabrication of a two-part textile antenna," *Textile Res. J.*, vol. 89, no. 4, pp. 560–571, 2018.
[53] D.-Y. Shin, Y. Lee, and C. H. Kim, "Performance characterization of screen printed radio frequency identification antennas with silver nanopaste," *Thin Solid Films*, vol. 517, pp. 6112–6118, Sep. 2009.
[54] H. Shahariar, H. Soewardiman, C. A. Muchler, J. J. Adams, and J. S. Jur, "Porous textile antenna designs for improved wearability," *Smart Mater. Struct.*, vol. 27, no. 4, 2018, Art. no. 045008.
[55] B. Li, D. Li, and J. Wang, "Copper deposition on textiles via an automated dispensing process for flexible microstrip antennas," *Textile Res. J.*, vol. 84, pp. 2026–2035, Jun. 2014.
[56] D. Xu, X. Tian, X. Guo, W. Jiang, W. Liu, and S. Xing, "Design and research of flexible wearable textile antenna based on GNPs/PANI/PDMS composites for 2.45 GHz," *Nanosci. Nanotechnol. Lett.*, vol. 9, no. 4, pp. 476–480, 2017.
[57] S. Ahmed, F. A. Tahir, A. Shamim, and H. M. Cheema, "A compact kapton-based inkjet-printed multiband antenna for flexible wireless devices," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 1802–1805, 2015.

[58] M. Akbari, M. W. A. Khan, M. Hasani, T. Björninen, L. Sydänheimo, and L. Ukkonen, ''Fabrication and characterization of graphene antenna for low-cost and environmentally friendly RFID tags,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1569–1572, 2016.
[59] Z. Stempien, E. Rybicki, T. Rybicki, and J. Lesnikowski, ''Inkjet-printing deposition of silver electro-conductive layers on textile substrates at low sintering temperature by using an aqueous silver ions-containing ink for textronic applications,'' *Sens. Actuators B, Chem.*, vol. 224, pp. 714–725, Mar. 2016.
[60] H. R. Khaleel, ''Design and fabrication of compact inkjet printed antennas for integration within flexible and wearable electronics,'' *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 4, no. 10, pp. 1722–1728, Oct. 2014.
[61] T. Fujimoto. (2010). *Dimatix Materials Printer DMP-2831*. [Online]. Available: http://www.fujifilmusa.com/shared/bin/DMP-2831_Datasheet_05-13.pdf
[62] W. G. Whittow *et al.*, ''Inkjet-printed microstrip patch antennas realized on textile for wearable applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 71–74, Jan. 2014.
[63] Z. Stempien, E. Rybicki, A. Patykowska, T. Rybicki, and M. I. Szynkowska, ''Shape-programmed inkjet-printed silver electro-conductive layers on textile surfaces,'' *J. Ind. Textiles*, vol. 47, pp. 1321–1341, Jan. 2017.
[64] M. Grouchko, A. Kamyshny, C. F. Mihailescu, D. F. Anghel, and S. Magdassi, ''Conductive inks with a 'built-in' mechanism that enables sintering at room temperature,'' *ACS Nano*, vol. 5, pp. 3354–3359, Mar. 2011.
[65] K. Black, J. Singh, D. Mehta, S. Sung, C. J. Sutcliffe, and P. R. Chalker, ''Silver ink formulations for sinter-free printing of conductive films,'' *Sci. Rep.*, vol. 6, Feb. 2016, Art. no. 20814.
[66] K. N. Paracha, S. K. A. Rahim, H. T. Chattha, S. S. Aljaafreh, S. U. Rehman, and Y. C. Lo, ''Low-cost printed flexible antenna by using an office printer for conformal applications,'' *Int. J. Antennas Propag.*, vol. 2018, Feb. 2018, Art. no. 3241581.
[67] Z. H. Jiang, Z. Cui, T. Yue, Y. Zhu, and D. H. Werner, ''Compact, highly efficient, and fully flexible circularly polarized antenna enabled by silver nanowires for wireless body-area networks,'' *IEEE Trans. Biomed. Circuits Syst*, vol. 11, no. 4, pp. 920–932, Aug. 2017.
[68] T. Kaufmann and C. Fumeaux, ''Wearable textile half-mode substrate-integrated cavity antenna using embroidered vias,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 805–808, 2013.
[69] Z. H. Jiang, D. E. Brocker, P. E. Sieber, and D. H. Werner, ''A compact, low-profile metasurface-enabled antenna for wearable medical body-area network devices,'' *IEEE Trans. Antennas Propag.*, vol. 62, no. 8, pp. 4021–4030, Aug. 2014.
[70] B. Hu, G.-P. Gao, L.-L. He, X.-D. Cong, and J.-N. Zhao, ''Bending and on-arm effects on a wearable antenna for 2.45 GHz body area network,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 378–381, 2016.
[71] T. Inui, H. Koga, M. Nogi, N. Komoda, and K. Suganuma, ''A miniaturized flexible antenna printed on a high dielectric constant nanopaper composite,'' *Adv. Mater.*, vol. 27, pp. 1112–1116, Feb. 2015.
[72] B. Mandal and S. K. Parui, ''A miniaturized wearable button antenna for Wi-Fi and Wi-Max application using transparent acrylic sheet as substrate,'' *Microw. Opt. Technol. Lett.*, vol. 57, pp. 45–49, Jan. 2015.
[73] S. J. Chen, T. Kaufmann, D. C. Ranasinghe, and C. Fumeaux, ''A modular textile antenna design using snap-on buttons for wearable applications,'' *IEEE Trans. Antennas Propag.*, vol. 64, no. 3, pp. 894–903, Mar. 2016.
[74] S. J. Chen, C. Fumeaux, D. C. Ranasinghe, and T. Kaufmann, ''Paired snap-on buttons connections for balanced antennas in wearable systems,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 14, no. , pp. 1498–1501, 2015.
[75] Y. S. Chen and T.-Y. Ku, ''A low-profile wearable antenna using a miniature high impedance surface for smartwatch applications,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1144–1147, 2016.
[76] J. Tak, Y. Hong, and J. Choi, ''Textile antenna with EBG structure for body surface wave enhancement,'' *Electron. Lett.*, vol. 51, no. 15, pp. 1131–1132, Jul. 2015.
[77] M. Ramzan and K. Topalli, ''A miniaturized patch antenna by using a CSRR loading plane,'' *Int. J. Antennas Propag.*, vol. 2015, Jul. 2015, Art. no. 495629.
[78] X. Y. Liu, Z. T. Wu, Y. Fan, and E. M. Tentzeris, ''A miniaturized CSRR loaded wide-beamwidth circularly polarized implantable antenna for subcutaneous real-time glucose monitoring,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 577–580, 2017.
[79] S.-W. Su and C.-T. Lee, ''Metal-frame GPS antenna for smartwatch applications,'' *Prog. Electromagn. Res. Lett.*, vol. 62, pp. 41–47, Sep. 2016.
[80] H. Lee, J. Tak, and J. Choi, ''Wearable antenna integrated into military berets for indoor/outdoor positioning system,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1919–1922, 2017.
[81] M. Jais, M. F. Jamlos, M. Jusoh, T. Sabapathy, and M. R. Kamarudin, ''A novel 1.575-GHz dual-polarization textile antenna for GPS application,'' *Microw. Opt. Technol. Lett.*, vol. 55, pp. 2414–2420, Oct. 2013.
[82] A. Dierck, H. Rogier, and F. Declercq, ''An active wearable dual-band antenna for GPS and Iridium satellite phone deployed in a rescue worker garment,'' in *Proc. IEEE Int. Conf. RFID-Technol. Appl. (RFID-TA)*, Sep. 2013, pp. 1–5.
[83] M. Joler and M. Boljkovac, ''A sleeve-badge circularly polarized textile antenna,'' *IEEE Trans. Antennas Propag.*, vol. 66, no. 3, pp. 1576–1579, Mar. 2018.
[84] K. Saurav, D. Sarkar, and K. V. Srivastava, ''Dual-polarized dual-band patch antenna loaded with modified mushroom unit cell,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1357–1360, 2014.
[85] N. Nasimuddin, X. Qing, and Z. N. Chen, ''A compact circularly polarized slotted patch antenna for GNSS applications,'' *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, pp. 6506–6509, Dec. 2014.
[86] M.-A. Chung and C.-F. Yang, ''Built-in antenna design for 2.4 GHz ISM band and GPS operations in a wrist-worn wireless communication device,'' *IET Microw., Antennas Propag.*, vol. 10, no. 12, pp. 1285–1291, 2016.
[87] M. Fernandez, H. G. Espinosa, D. V. Thiel, and A. Arrinda, ''Wearable slot antenna at 2.45 GHz for off-body radiation: Analysis of efficiency, frequency shift, and body absorption,'' *Bioelectromagnetics*, vol. 39, pp. 25–34, Jan. 2018.
[88] H. Bahramiabarghouei, E. Porter, A. Santorelli, B. Gosselin, M. Popović, and L. A. Rusch, ''Flexible 16 antenna array for microwave breast cancer detection,'' *IEEE Trans Biomed Eng*, vol. 62, no. 10, pp. 2516–2525, Oct. 2015.
[89] *IEEE Standards Coordinating Committee 28, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3kHz to 300 GHz*, 1999th ed., IEEE Standard C95.1, Institute of Electrical and Electonics Engineers, 1992.
[90] The International Commission on Non-Ionizing Radiation Protection, ''Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz),'' *Health Phys.*, vol. 74, no. 4, pp. 494–522, Apr. 1998.
[91] A. Cihangir, W. Whittow, C. Panagamuwa, G. Jacquemod, F. Gianesello, and C. Luxey, ''4G antennas for wireless eyewear devices and related SAR,'' *Comp. Rendus Phys.*, vol. 16, pp. 836–850, Nov. 2015.
[92] M. I. Kitra, C. J. Panagamuwa, P. McEvoy, J. C. Vardaxoglou, and J. R. James, ''Low SAR ferrite handset antenna design,'' *IEEE Trans. Antennas Propag.*, vol. 55, no. 4, pp. 1155–1164, Apr. 2007.
[93] N. Gunavathi and D. Sriramkumar, ''CPW-fed monopole antenna with reduced radiation hazards toward human head using metallic thin-wire mesh for 802.11ac applications,'' *Microw. Opt. Technol. Lett.*, vol. 57, pp. 2684–2687, Nov. 2015.
[94] E. Rajo-Iglesias, I. Gallego-Gallego, L. Inclan-Sanchez, and O. Quevedo-Teruel, ''Textile soft surface for back radiation reduction in bent wearable antennas,'' *IEEE Trans. Antennas Propag.*, vol. 62, no. 7, pp. 3873–3878, Jul. 2014.
[95] K. W. Lui, O. H. Murphy, and C. Toumazou, ''A wearable wideband circularly polarized textile antenna for effective power transmission on a wirelessly-powered sensor platform,'' *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3873–3876, Jul. 2013.
[96] C. Loss, R. Gonçalves, C. Lopes, P. Pinho, and R. Salvado, ''Smart coat with a fully-embedded textile antenna for IoT applications,'' *Sensors*, vol. 16, no. 6, p. 938, 2016.
[97] L. A. Y. Poffelie, P. J. Soh, S. Yan, and G. A. E. Vandenbosch, ''A high-fidelity all-textile UWB antenna with low back radiation for off-body WBAN applications,'' *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 757–760, Feb. 2016.
[98] K. Agarwal, Y.-X. Guo, and B. Salam, ''Wearable AMC backed near-endfire antenna for on-body communications on latex substrate,'' *IEEE Trans. Compon., Packag. Manuf. Technol.*, vol. 6, no. 3, pp. 346–358, Mar. 2016.
[99] K. N. Paracha *et al.*, ''A low profile, dual-band, dual polarized antenna for indoor/outdoor wearable application,'' *IEEE Access*, vol. 7, pp. 33277–33288, 2019.

[100] M. Mantash, A.-C. Tarot, S. Collardey, and K. Mahdjoubi, "Investigation of flexible textile antennas and AMC reflectors," *Int. J. Antennas Propag.*, vol. 2012, Feb. 2012, Art. no. 236505.

[101] H. R. Raa, A. I. Abbosh, H. M. Al-Rizzo, and D. G. Rucker, "Flexible and compact AMC based antenna for telemedicine applications," *IEEE Trans. Antennas Propag.*, vol. 61, no. 2, pp. 524–531, Feb. 2013.

[102] F. N. Giman *et al.*, "Conformal dual-band textile antenna with metasurface for WBAN application," *Appl. Phys. A, Solids Surf.*, vol. 123, p. 32, Jan. 2016.

[103] V. Karthik and T. R. Rao, "Investigations on SAR and thermal effects of a body wearable microstrip antenna," *Wireless Pers. Commun.*, vol. 96, pp. 3385–3401, Oct. 2017.

[104] M. V. Varnoosfaderani, D. V. Thiel, and J. Lu, "External parasitic elements on clothing for improved performance of wearable antennas," *IEEE Sensors J.*, vol. 15, no. 1, pp. 307–315, Jan. 2015.

[105] N. Gunavathi and D. S. Kumar, "Miniaturized unilateral coplanar waveguide-fed asymmetric planar antenna with reduced radiation hazards for 802.11AC applications," *Microw. Opt. Technol. Lett.*, vol. 58, pp. 467–471, Feb. 2016.

[106] S. Velan *et al.*, "Dual-band EBG integrated monopole antenna deploying fractal geometry for wearable applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 249–252, 2015.

[107] S. J. Chen, B. Chivers, R. Shepherd, and C. Fumeaux, "Bending impact on a flexible ultra-wideband conductive polymer antenna," in *Proc. Int. Conf. Electromagn. Adv. Appl. (ICEAA)*, 2015, pp. 422–425.

[108] S. M. Salleh, M. Jusoh, A. H. Ismail, M. N. M. Yasin, M. R. Kamarudin, and R. Yahya, "Circular polarization textile antenna for GPS application," in *Theory and Applications of Applied Electromagnetics*. Cham, Switzerland: Springer, 2015, pp. 255–263.

[109] P. Salonen and Y. Rahimat-Samii, "Textile antennas: Effects of antenna bending on input matching and impedance bandwidth," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 22, no. 3, pp. 10–14, Mar. 2007.

[110] S. M. Saeed, C. A. Balanis, C. R. Birtcher, A. C. Durgun, and H. N. Shaman, "Wearable flexible reconfigurable antenna integrated with artificial magnetic conductor," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2396–2399, 2017.

[111] S. M. Saeed, C. A. Balanis, and C. R. Birtcher, "Inkjet-printed flexible reconfigurable antenna for conformal WLAN/WiMAX wireless devices," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1979–1982, 2016.

[112] E. F. N. M. Hussin, P. J. Soh, M. F. Jamlos, H. Lago, A. A. Al-Hadi, and M. H. F. Rahiman, "A wideband textile antenna with a ring-slotted AMC plane," *Appl. Phys. A, Solids Surf.*, vol. 123, p. 46, Jan. 2016.

[113] K. Alzoubi, M. M. Hamasha, M. Schadt, S. Lu, B. Sammakia, and M. Poliks, "Effect of lamination on the bending fatigue life of copper coated PET substrate," *Proc. SPIE*, vol. 7956, pp. 79560X-1–79560X-9, Feb. 2011.

[114] L. Song and Y. Rahmat-Samii, "A systematic investigation of rectangular patch antenna bending effects for wearable applications," *IEEE Trans. Antennas Propag.*, vol. 66, no. 5, pp. 2219–2228, May 2018.

[115] Q. Bai and R. Langley, "Wearable EBG antenna bending and crumpling," in *Proc. Loughborough Antennas Propag. Conf.*, 2009, pp. 201–204.

[116] E. K. Kaivanto, M. Berg, E. Salonen, and P. de Maagt, "Wearable circularly polarized antenna for personal satellite communication and navigation," *IEEE Trans. Antennas Propag.*, vol. 59, no. 12, pp. 4490–4496, Dec. 2011.

[117] X. L. Yang, J. C. Lin, G. Chen, and F. L. Kong, "Frequency reconfigurable antenna for wireless communications using GaAs FET switch," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, no. , pp. 807–810, Dec. 2015.

[118] H. Zhai, L. Liu, C. Zhan, and C. Liang, "A frequency-reconfigurable triple-band antenna with lumped components for wireless applications," *Microw. Opt. Technol. Lett.*, vol. 57, pp. 1374–1379, Jun. 2015.

[119] M. W. Young, S. Yong, and J. T. Bernhard, "A miniaturized frequency reconfigurable antenna with single bias, dual varactor tuning," *IEEE Trans. Antennas Propag.*, vol. 63, no. 3, pp. 946–951, Mar. 2015.

[120] H. F. Abutarboush and A. Shamim, "A Reconfigurable inkjet-printed antenna on paper substrate for wireless applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, pp. 1648–1651, 2018.

[121] S. F. Jilani, A. Rahimian, Y. Alfadhl, and A. Alomainy, "Low-profile flexible frequency-reconfigurable millimetre-wave antenna for 5G applications," *Flexible Printed Electron.*, vol. 3, no. 3, 2018, Art. no. 035003.

[122] J. Kumar, B. Basu, F. A. Talukdar, and A. Nandi, "Graphene-based multimode inspired frequency reconfigurable user terminal antenna for satellite communication," *IET Commun.*, vol. 12, pp. 67–74, Jan. 2018.

[123] S. M. Salleh *et al.*, "Textile antenna with simultaneous frequency and polarization reconfiguration for WBAN," *IEEE Access*, vol. 6, pp. 7350–7358, 2018.

[124] G. Bo, L. Ren, X. Xu, Y. Du, and S. Dou, "Recent progress on liquid metals and their applications," *Adv. Phys., X*, vol. 3, Mar. 2018, Art. no. 1446359.

[125] A. P. Saghati, J. Batra, J. Kameoka, and K. Entesari, "A microfluidically-switched CPW folded slot antenna," in *Proc. IEEE Antennas Propag. Soc. Int. Symp. (APSURSI)*, Jul. 2014, pp. 557–558.

[126] A.-P. Saghati, J.-S. Batra, J. Kameoka, and K. Entesari, "Miniature and reconfigurable CPW folded slot antennas employing liquid-metal capacitive loading," *IEEE Trans. Antennas Propag.*, vol. 63, no. 9, pp. 3798–3807, Sep. 2015.

[127] M. S. Anwar and A. Bangert, "3D printed microfluidics-based reconfigurable antenna," in *Proc. IEEE MTT-S Int. Microw. Workshop Ser. Adv. Mater. Processes RF THz Appl. (IMWS-AMP)*, Sep. 2017, pp. 1–3.

[128] C. Wang, J. C. Yeo, H. Chu, C. T. Lim, and Y.-X. Guo, "Design of a reconfigurable patch antenna using the movement of liquid metal," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 6, pp. 974–977, Jun. 2018.

[129] S. Lemey, S. Agneessens, and H. Rogier, "Wearable smart objects: Microwaves propelling smart textiles: A review of holistic designs for wireless textile nodes," *IEEE Microw. Mag.*, vol. 19, no. 6, pp. 83–100, Sep./Oct. 2018.

[130] S. B. Vignesh, Nasimuddin, and A. Alphones, "Circularly polarized strips integrated microstrip antenna for energy harvesting applications," *Microw. Opt. Technol. Lett.*, vol. 58, pp. 1044–1049, May 2016.

[131] D. Masotti, A. Costanzo, and S. Adami, "Design and realization of a wearable multi-frequency RF energy harvesting system," in *Proc. 5th Eur. Conf. Antennas Propag. (EUCAP)*, 2011, pp. 517–520.

[132] A. Collado and A. Georgiadis, "Conformal hybrid solar and electromagnetic (EM) energy harvesting rectenna," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 60, no. 8, pp. 2225–2234, Aug. 2013.

[133] H. Kanaya, S. Tsukamaoto, T. Hirabaru, D. Kanemoto, R. K. Pokharel, and K. Yoshida, "Energy harvesting circuit on a one-sided directional flexible antenna," *IEEE Microw. Wireless Compon. Lett.*, vol. 23, no. 3, pp. 164–166, Mar. 2013.

[134] G. Monti, L. Corchia, and L. Tarricone, "UHF wearable rectenna on textile materials," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3869–3873, Jul. 2013.

[135] V. Palazzi *et al.*, "A novel ultra-lightweight multiband rectenna on paper for RF energy harvesting in the next generation LTE bands," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 1, pp. 366–379, Jan. 2018.

[136] S.-E. Adami *et al.*, "A flexible 2.45-GHz power harvesting wristband with net system output from -24.3 dBm of RF power," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 1, pp. 380–395, Jan. 2018.

[137] H. Xiaomu, S. Yan, and G. A. E. Vandenbosch, "Wearable button antenna for dual-band WLAN applications with combined on and off-body radiation patterns," *IEEE Trans. Antennas Propag.*, vol. 65, no. 3, pp. 1384–1387, Mar. 2017.

[138] X. Y. Zhang, H. Wong, T. Mo, and Y. F. Cao, "Dual-band dual-mode button antenna for on-body and off-body communications," *IEEE Trans. Biomed. Circuits Syst.*, vol. 11, no. 4, pp. 933–941, Aug. 2017.

[139] Q. Liu, T. Le, S. He, and M. Tentzeris, "Button-shaped radio-frequency identification tag combining three-dimensional and inkjet printing technologies," *IET Microw. Antennas Propag.*, vol. 10, no. 7, pp. 737–741, 2016.

[140] M. Mantash, A. C. Tarot, S. Collardey, and K. Mahdjoubi, "Wearable monopole zip antenna," *Electron. Lett.*, vol. 47, no. 23, pp. 1266–1267, Nov. 2011.

[141] G. Li, Y. Huang, G. Gao, X. Wei, Z. Tian, and L. A. Bian, "A handbag zipper antenna for the applications of body-centric wireless communications and Internet of Things," *IEEE Trans. Antennas Propag.*, vol. 65, no. 10, pp. 5137–5146, Oct. 2017.

[142] G. Li, Z. Tian, G. Gao, L. Zhang, M. Fu, and Y. Chen, "A shoelace antenna for the application of collision avoidance for the blind person," *IEEE Trans. Antennas Propag.*, vol. 65, no. 9, pp. 4941–4946, Sep. 2017.

[143] C.-H. Wu, J.-S. Sun, and B.-S. Lu, "Watchstrap-embedded four-element multiple-input–multiple-output antenna design for a smartwatch in 5.2–5.8 GHz wireless applications," *Int. J. Antennas Propag.*, vol. 2018, Apr. 2018, Art. no. 1905984.

[144] G. Li, G. Gao, J. Bao, B. Yi, C. Song, and L.-A. Bian, "A watch strap antenna for the applications of wearable systems," *IEEE Access*, vol. 5, no. 5, pp. 10332–10338, May 2017.

[145] D. Wu and S. W. Cheung, "A cavity-backed annular slot antenna with high efficiency for smartwatches with metallic housing," *IEEE Trans. Antennas Propag.*, vol. 65, no. 7, pp. 3756–3761, Jul. 2017.
[146] M. Mantash and T. Denidni, "Finger-worn end-fire antenna for MM-wave applications," *Microw. Opt. Technol. Lett.*, vol. 59, pp. 2591–2593, Oct. 2017.
[147] S. Hong, S. H. Kang, Y. Kim, and C. W. Jung, "Transparent and flexible antenna for wearable glasses applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2797–2804, Jul. 2016.
[148] A. Cihangir, F. Gianesello, and C. Luxey, "Dual-antenna concept with complementary radiation patterns for eyewear applications," *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 3056–3063, Jun. 2018.
[149] Y. Hong and J. Choi, "60 GHz patch antenna array with parasitic elements for smart glasses," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 7, pp. 1252–1256, Jul. 2018.

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