Mini Review

Wearable textile antennas

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With the ongoing miniaturization of wireless devices, the importance of wearable textiles in the antenna segment has increased significantly in recent years. Due to the widespread utilization of wireless body sensor networks for healthcare and ubiquitous applications, the design of wearable antennas offers the possibility of comprehensive monitoring, communication, and energy harvesting and storage. This article reviews a number of properties and benefits to realize comprehensive background information and application ideas for the development of lightweight, compact and low-cost wearable patch antennas. Furthermore, problems and challenges that arise are addressed. Since both electromagnetic and mechanical specifications must be fulfilled, textile and flexible antennas require an appropriate trade-off between materials, antenna topologies, and fabrication methods—depending on the intended application and environmental factors. This overview covers each of the above issues, highlighting research to date while correlating antenna topology, feeding techniques, textile materials, and contacting options for the defined application of wearable planar patch antennas.

The widespread and growing interest in integrating clothing into the communication system, is nowadays mainly driven by new concepts such as the Internet of Things (IoT). This involves the identifiability, communication and interaction of objects. Several electronic components such as batteries, sensors, actuators, data processing units, connectors and antennas define a wireless communication system. In this context, the term electronic textiles (e-textiles) is introduced. These are fabrics in which electronics and interconnections are woven [1]. One of the future goals is that textile antennas can replace the bulky antennas in e-textiles within IoT and 5G networks [2].

Planar antenna topologies are widely used for near-body communications due to their high body isolation, low profile, robustness, simple fabrication, and at the same time low cost. Textile materials, unlike conventional materials, offer better bending behavior, lower permittivity and less weight [3]. This, in combination with the planar topology, makes them an interesting option for near-body communication. Some small companies and startups are aiming to integrate electronics into clothing to make it more comfortable to wear without the need for additional devices.

According to this, the field of application is very versatile. Textile antennas are used, for example, in medical monitoring of patients [4,5], GPS sensing for personal safety [6], wireless information transmission [7], and sports [8]. Since the available space above the textile surface is large, they can also be used for energy harvesting [9]. Specific requirements for the design of wearable textile antennas are needed because planar and flexible textile substrates are now being used, which are generally not immediately associated with high-

frequency circuits. They must guarantee a comfortable and asthetically acceptable design as well as robust performance against bending, wrinkling, washing and ironing.
The approaches to the design and integration of the textile antennas encounter some difficulties. Therefore, the rest of the paper is organized as follows: Textile antennas present a current challenge in terms of suitable simulation models, which is discussed in "Project-specific application and challenges" section. In order to understand the necessary context, "Project-specific application and challenges" section additionally lists the different application areas as well as the advantages of textile antennas. Since the possible technologies for the production of textile antennas already play a role in the previous part, "Manufacturing techniques for textile antennas" section deals with the following manufacturing processes: Thin and uniform metallization layers, weaving and knitting, embroidery, inkjet and screen printing, and metallized nonwovens. The selection of the most suitable conductive thread in terms of conductivity, strength and flexibility is also discussed in the literature. Further on in the paper, we will deal with the key properties of conductive filaments. One of the most important parameters is the surface resistance, which has an impact on the performance of the antenna. Furthermore, "Characterization of conductive materials" section also deals with electrically conductive hybrid yarns that combine the properties of two or more fibers. Nowadays, the development of conductive hybrid yarns is one of the most important research areas to meet the various requirements of functional textiles. Another challenge facing the designer of a textile antenna concerns the choice of a suitable antenna topology. Here, a variety of conflicting electrical and mechanical requirements must be reconciled. Depending on the operating frequency and the particular application, the focus is on knitted patch antennas as we will deal with it in future works ("Possible Antenna Topology for defined application area" section). In order to simultaneously meet the mechanical requirements for robustness while ensuring high Radio Frequency (RF) performance, the choice of a suitable feeding technique for textile antennas is crucial. There are several ways to feed a patch antenna, among which we discuss coaxial probe feeding, microstrip line feed, aperture coupled feed, and proximity coupled feed in "Feeding techniques for patch antennas" section. Also, the connection between flexible textiles and stiff electronic components has always been structurally weak and a limiting factor in the establishment of smart textiles in our everyday life. Therefore, "Contacting Options for Electronic Textiles" section focuses on the fabrication of reliable connections between conductive textiles and conventional electronic components. Both advantages and disadvantages are compared and their behavior under load is analyzed.

Prospects and problems – Some perspectives

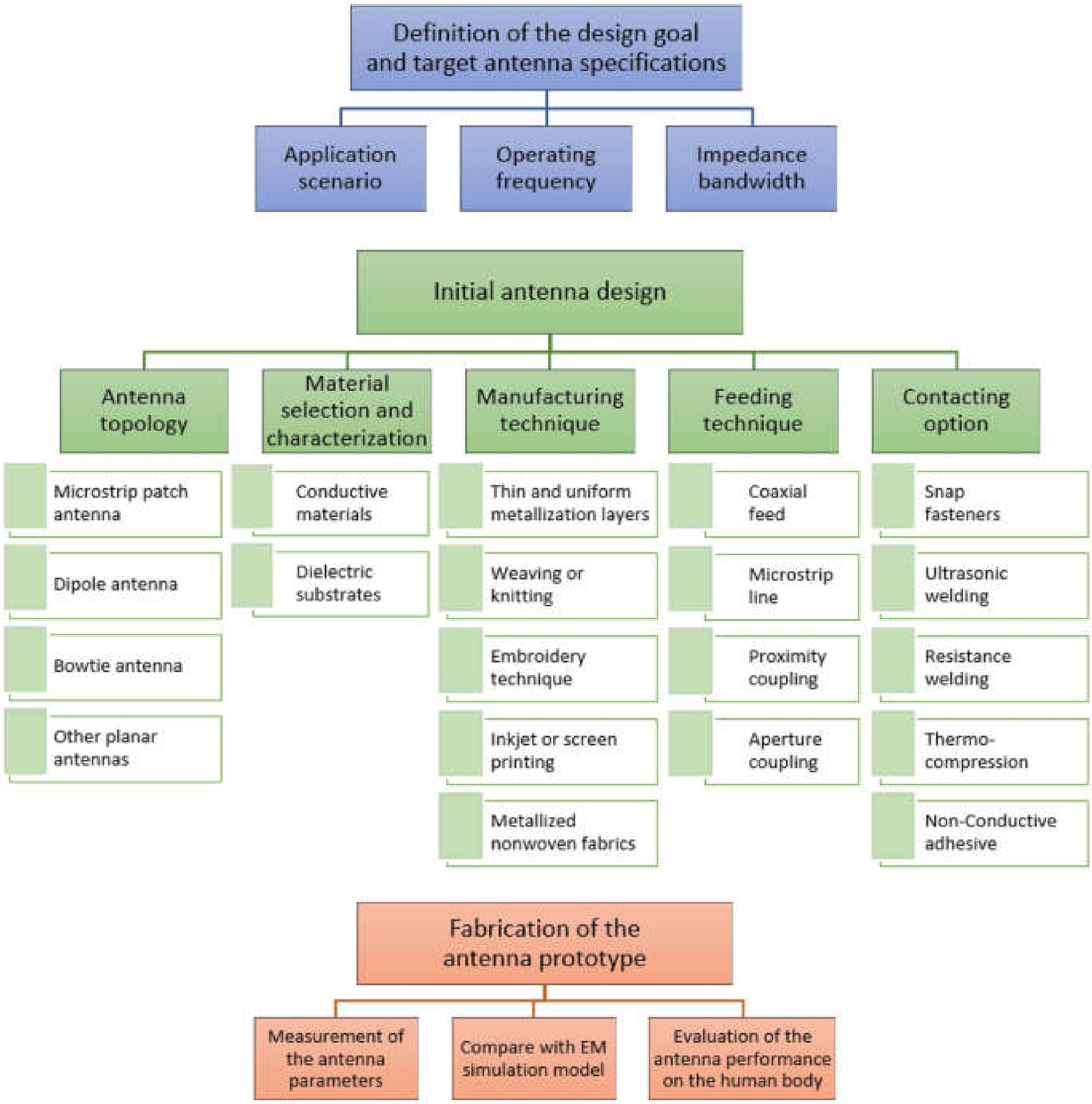
Future simulations and measurements will focus on developing textile antennas that can be used for wireless communication or as elastic sensors. Conceivable applications for the use of antennas as sensors would be the monitoring of respiratory rate to increase the safety of first responders or the long-term monitoring of the state of oedema and its progression during the day, which is currently not possible. This may lead to more effective medication. In order to get a comprehensive overview of the various production steps and procedures, the overall technological process for manufacturing a wearable antenna is illustrated in a scheme (Fig. 1) at the end of this section. The following paragraphs will then go into more detail.
A challenging design process of textile (sensor) antennas, which can be integrated into garments and sleeves, will be facilitated by simulations and the subsequent characterization. This enables a design process that considers the functional characterization of textile elements with sufficient precision prior to fabrication and testing. Understanding the high-

frequency electronic properties is key to the design and development of new applications based on textile structures.

The main difference between conventional metal-based and textile-based antennas is the conductive surface, which is continuous in the former case. This leads to high conductivity combined with a uniform electromagnetic (EM) field and thus high efficiency. Designing a high efficiency textile-based antenna is challenging due to the discontinuous and anisotropic surface. Some authors have already studied the efficiency of textile antennas: According to Locher et al. (2006) [10] a knitted antenna shows an efficiency of 45% whereas an antenna with a conductive metal wire woven into its fabric already reaches an efficiency of 78% [11]. However, the incorporation of the metal wires increases the manufacturing process and reduces the flexibility of the fabric. Literature indicates that both high conductivity and flexibility can be achieved by embroidering with conductive yarn [12].

Fundamentally, for the challenges presented above, it is important to understand how the conductive filaments change the current flow in the antenna at its operating frequency. The authors in Banaszczyk et al. (2007) [13] reported the current distribution under DC conditions on conductive fabric and pointed out that the sheet resistance of the fabric is affected by the fiber direction, the current direction, and the contact resistance. Accordingly, it is of great importance to analyze the respective structures of textile antennas in detail. Also, the analysis of the gaps between the yarns is crucial for the performance of textile antennas and depends on the textile structure ("Manufacturing techniques for textile antennas" section) as well as the diameter of the yarns. Due to these limitations, it is not easy to define an EM simulation model that accurately describes the characteristics of textile antennas. Therefore, the focus for future research is to efficiently develop material models that can be used to derive design rules.

Fig. 1



Overall technological process for manufacturing a wearable antenna

The technologies

The design and especially the manufacturing process of a wearable antenna are crucial to the antenna performance and production time. When selecting the appropriate method, good agreement between design and simulation results should be ensured, which in turn guarantees the robustness and reproducibility of a textile antenna. The manufacturing techniques can be categorized as follows:

- Thin and uniform metallization layers;
- Conductive textile yarns to weave or knit the conductive patterns;
- Conductive textile yarns to embroider the conductive patterns;
- Inkjet and screen printing onto non-conductive textile materials; and
- Deposition of metal coatings onto non-conductive nonwoven fabrics.

In addition, Table 1 provides an overview of the manufacturing processes commonly used in the literature with respect to textile antennas.

Textile antennas are one of the main elements of wearable and portable equipment design. They serve as platforms for body-centric sensing, localization and wireless communication systems owing to their lightweight, versatility, relatively inexpensive, and conformal features. The choice of manufacturing process and material variants for the conductive and non-conductive components of the textile antennas depend on the application.
During the course of the paper, thin and uniform metallization layers, methods such as weaving or embroidery with conductive textile yarns, inkjet and screen printing, and metal coatings on nonconductive nonwovens were addressed. It turns out that for applications requiring higher levels of stretch and bend, such as sportswear or the elastic textile sensors in medical applications covered within this review, knitted antennas offer potential advantages. The knit geometry imparts the elasticity required for mobility and comfort. Since these are near-body applications, the focus is on textile-based micro strip patch antennas as they provide adequate shielding from the human body. For these antenna topologies, a variety of feeding techniques have already been used (Coaxial Feed, Micro strip Line, Proximity Coupling, Aperture Coupling) to achieve the desired mechanical and EM performance. Furthermore, various techniques to improve BW have been reported.
The conductive fabrics for the patch and ground planes require very low electrical surface resistance to minimize electrical losses and thus increase antenna efficiency.
For the application area mentioned here, the focus is on hybrid conductive threads. The structure and key properties have been addressed, allowing wash-resistant, flexible and stretchable units to be developed. There are also several methods for connecting textiles to electronics. They can be divided into non-reversible (Ultrasonic Welding, Resistance Welding, Thermo compression Bonding, Non-Conductive Adhesive Bonding) and reversible methods (Snap Fastener).

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