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Wearable textile antennas: investigation on material variants, fabrication methods, design and application

Verena Marterer[1,2*], Michaela Radouchová[2†], Radek Soukup[2†], Susanne Hipp[1†] and Tomáš Blecha[2†]

[†]Michaela Radouchová, Radek Soukup, Susanne Hipp and Tomáš Blecha are contributed equally to this work.

*Correspondence: verena1.marterer@st.oth-regensburg.de

[1] Faculty of Electrical Engineering, Ostbayerische Technische Hochschule Regensburg, Seybothstraße 2, 93053 Regensburg, Germany
[2] Faculty of Electrical Engineering, University of West Bohemia, Univerzitní 8, 301 00 Pilsen, Czech Republic

Abstract

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.

Keywords: Textile antenna, Wearable communication, Patch antenna, Design requirements, Smart textiles, E-textiles

Introduction

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 (Stoppa & Chiolerio, 2014). One of the future goals is that textile antennas can replace the bulky antennas in e-textiles within IoT and 5G networks (Mukai & Suh, 2021).

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 (Salvado et al., 2012). 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 (Yadav et al., 2020; Song et al., 2021), GPS sensing for personal safety (Salonen et al. 2004), wireless information transmission (Wagih et al., 2021), and sports (Coyle et al., 2009). Since the available space above the textile surface is large, they can also be used for energy harvesting (Yamada, 2022). 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.

Literature review

Project-specific application and challenges

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

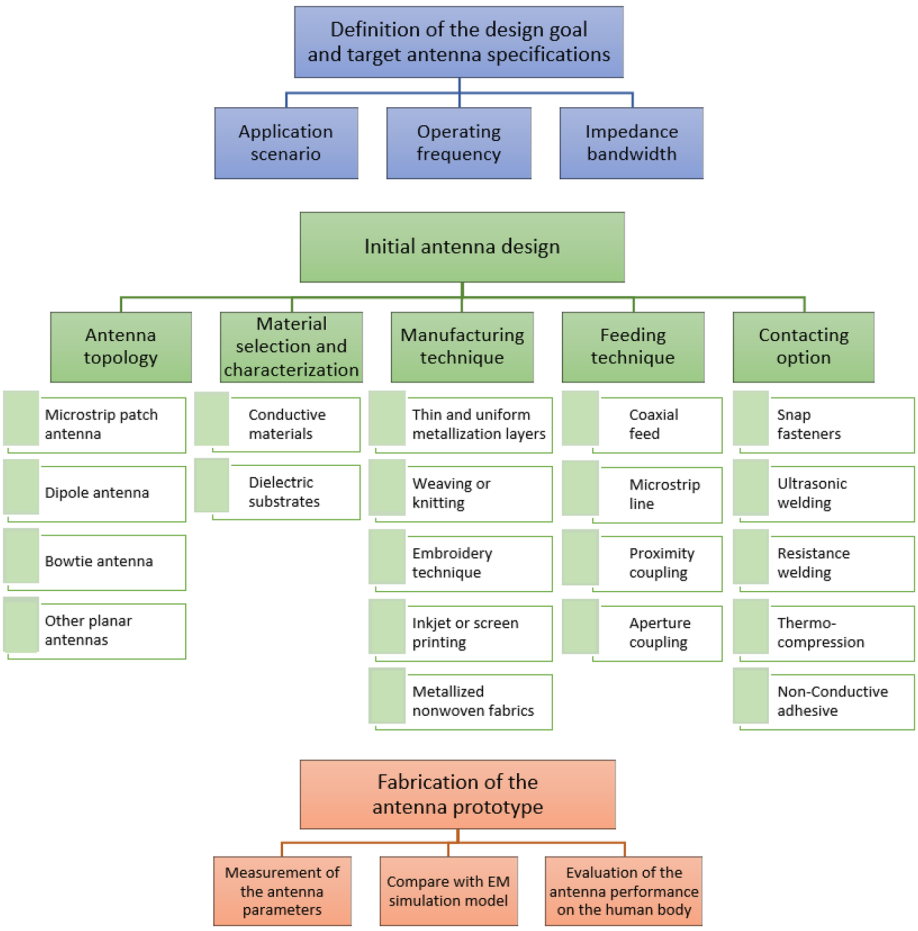


Fig. 1 Overall technological process for manufacturing a wearable antenna

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) 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% (Ouyang & Chappell, 2008). 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 (Wang et al., 2012).

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) 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.

Methods

Manufacturing techniques for textile antennas

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.

Thin and uniform metallization layers

Thin and uniform metallization layers on non-conductive textile substrates are a common method for producing textile antennas. The metal coating can be achieved either by

Table 1 Comparison of different manufacturing techniques for the fabrication of textile antennas and their advantages and disadvantages

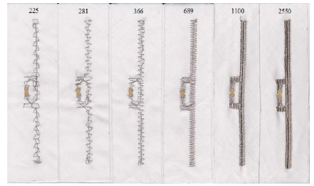
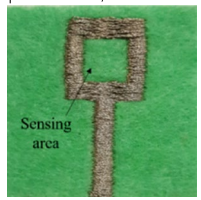
Reference	Manufacturing technique	Advantages	Disadvantages	Possibilities	Fabricated samples
Wang et al. (2015); Bulathsinghala (2022)	Embroidered Antennas	*Mechanical flexability* No problems related to cracks and deformations due to mechanical stress *Remarkable RF performance* No compromis on antenna performance and efficiency *Sheet resistance can be adjusted* Controlling stitch spacing, stitch length, stitch direction and/or stitch pattern *Avoiding additional assembling process* Pattern can be directly transferred onto the fabric	*Affects geometry accuracy and geometry resolution* Especially at corners and edges *Separate assembly process required to manufacture patch antennas* *Avoid sewing needle breakage from mechanical fatigue* Especially challenging for denser or multi-layer embroideries	RFID Personal protective clothing IoT networks	 Wearable embroidered dipole-type ultra high frequency (UHF) RFID tag antennas (© [2012] IEEE. Reprinted, with permission, from Moradi et al. (2012))  Microwave antenna-based sensor for in vitro experiments for monitoring blood glucose levels (Gharbi et al. 2021)

Table 1 (continued)

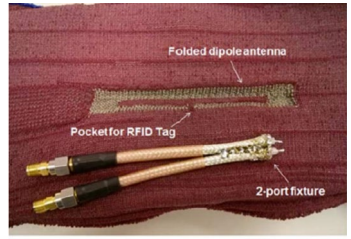
Reference	Manufacturing technique	Advantages	Disadvantages	Possibilities	Fabricated samples
Bulathsinghala (2022)	Knitted Antennas	*Sufficient elasticity for stretchable antenna systems* *One-step integration process of conductive and non-conductive yarns* Eliminates the degradation in antenna performance due to bulkiness and electrical losses (only for planar antennas like dipoles, manufactured in a one-step knitting process) *3D spatial fabrication technique possible* Entire antenna design—the radiating patch, ground plane, and dielectric substrate—can be knitted in a single process	*Inconsistent loop geometry within the structure* Depends on a combination of several parameters, such as take-down tension, feeding tension, knit structure, loop density, linear yarn density, etc. *Significant fluctuations in sheet resistance/conduction due to the stretching effect* Stretch on both axis possible: y-axis and x-axis *Increased conduction losses, due to non-uniform conductivity* Point connection of adjacent loops *Mechanical stabilization is essential* To maintain geometric accuracy	*Applications with a higher level of stretching and bending, such as sportswear* Knitting geometry imparts the required elasticity for mobility and comfort *Single jersey structures* Enables to fabricate planar complex topologies with minimal bulkiness and fewer heterogeneities (e.g. radiating patches and ground planes)	a)  b)  Strain sensor consisting of a folded, knitted dipole antenna equipped with an inductively coupled RFID tag (© [2016] IEEE. Reprinted, with permission, from Patron et al. (2016))

Table 1 (continued)

Reference	Manufacturing technique	Advantages	Disadvantages	Possibilities	Fabricated samples
Tsolis et al. (2014); Chauraya et al. (2013)	Printed Antennas	*Additive process* Does not require environmentally harmful etching chemicals *Excellent resolution* Leads to a high degree of reproducibility *Minimum material consumption* Cost-effective method of creating conductive patterns on different textile substrates	*Difficult to create continuous highly conductive traces* Rough, porous surface structure of textiles *Lower wash resistance* Ink can wear off over time *Low resistance to stretching and self-motion* *Resilience to high temperatures* Ink has a high percentage (≈ 85%) of non-conductive solvent to ensure inkjet printability—for this requirement this must be removed from the ink *Difficult to achieve high antenna efficiency*	Structural and health monitoring systems Wireless monitoring of vital functions	 Screen-printed coplanar keyhole antenna on fabric (Nylon/Spandex) substrate (Hasni et al. 2021)  Inkjet-printed 2.4 GHz Dipole antenna on polyurethane coated stretchable textile (Li et al. 2012)

attaching copper or silver tape, or by applying metal foils onto the textile fabric. This is a relatively simple and fast process compared to other methods that require more steps, such as weaving or knitting conductive textile yarns.

The thickness of the metallization layer is critical to the antenna's performance as it affects the electrical properties of the antenna, including its impedance and radiation efficiency.

One advantage of this technique is that it can easily be integrated into existing textile manufacturing processes such as printing, which can lower production costs and increase scalability. In addition, the use of thin and uniform metallization layers enables the production of antennas with a wide range of shapes and sizes, especially for simple geometries that do not require high precision.

There are also some challenges associated with this technique, such as the adhesion of the metal to the textile substrate, which can affect the antenna's durability. Factors such as bending or environmental conditions including moisture and heat come into play (Tsolis et al., 2014). Additionally, the choice of metal and thickness of the metallization layer must be carefully selected to ensure optimal performance, which may require extensive testing and optimization.

Weaving and knitting with conductive textile yarns

Conductive textile yarns can be used to weave or knit the patterns of antennas. This method is often used in the production of complex and precise antenna geometries where the idea of applying metal layers or printed patterns is insufficient. The use of conductive textile yarns for knitting or weaving antennas allows for a certain tolerance and flexibility in the structure (Tsolis et al., 2014). Compared to other methods, this provides better adaptability to different antenna shapes and sizes. For knitted or woven structures, it is possible to vary different parameters to thereby meet specific performance requirements. For example, wale and course density of knitted fabrics or warp and weft density of woven fabrics can be modified, as well as the yarn diameter.

When using weaving techniques, the yarns are woven horizontally and vertically to create a flat and dense structure. The threads are twisted into a cross pattern, so two sets of yarns are used. When knitting, the threads run parallel to each other and form loops. These loops can be arranged in different patterns and densities. Qualitatively, this means that knitted fabrics are more elastic, as the threads run one after the other in each row. Woven fabrics are less stretchy because the threads are interwoven in a crosswise pattern (Almohammed et al., 2021).

Embroidery technique for creating conductive patterns

Another way of applying conductive patterns to textiles is to embroider them using conductive textile yarns. The conductive threads form the antenna pattern on the textile fabric, while the non-conductive fabric serves as the substrate.

Embroidered textile antennas can be seamlessly integrated into garments and other textiles without being noticeable or distracting. As a result, they may be used in a variety of applications, such as consumer electronics or medicine (Ramya et al., 2021; Osman et al., 2011), without detracting from the aesthetics of the product. Furthermore, it offers

the advantage of being a relatively simple and cost-effective technique that does not require additional materials such as adhesives or metal layers.

However, precision is limited with this process, although this limitation can be partially addressed through the use of computer-assisted embroidery. Furthermore, embroidered textiles usually exhibit an anisotropic pattern. The conductivity depends not only on the current flow of the pattern, but also on the geometry, stitch direction, and stitch density. Higher antenna efficiencies can be achieved when the main current flow is parallel to the stitch direction. This can lead to further challenges if the design is to work at higher modes where the current flows in the perpendicular direction (Tsolis et al., 2014). In addition, efficiency is also increased by using a narrower stitch spacing. However, this leads to less flexibility and a longer yarn length, which in turn is associated with higher manufacturing costs.

Inkjet and screen printing onto non-conductive textiles

Inkjet and screen printing methods use conductive ink to print the antenna pattern onto non-conductive textile materials. Screen printing requires a mask that can be reused, but it is not a practical solution for different individual designs. Inkjet printing eliminates the need for masks, increasing flexibility in pattern creation (Tsolis et al., 2014). However, inkjet printing is typically slower and more expensive than screen printing. The choice of printing method depends on the specific application requirements. For example, screen printing is often used to produce RFID antennas on textiles (Kellomäki et al., 2012).

There are different types of electrically conductive inks available on the market for various applications. These inks are designed to be easily printed with a conventional color printer. Examples of conductive inks include carbon nanotubes, polymers, and metallic nanoparticles (Mehmann et al., 2017).

Antennas made by this process have lower wash resistance as the ink can wear off over time. Conductive ink can be protected with a breathable thermoplastic to ensure stable performance after multiple washing cycles. Printing on rough surfaces such as textiles is generally challenging as they are porous materials that make it difficult to create continuous highly conductive traces. Further challenges, such as resistance to stretching and self-motion as well as resistance to high temperatures required to remove the non-conductive solvent from the ink, must be considered in this method. In the literature, there are initial experiments with dipoles (Chauraya et al., 2013) and patch antennas (Whittow et al., 2014) that reduce the inherent surface roughness of cotton fabric by using a screen-printed intermediate layer. This allows printing antennas with reasonable efficiency with only one or two ink layers. The performance of the antenna can be improved by printing multiple layers, but this increases material costs and manufacturing time and decreases line resolution. Since the ink layer is thin, issues regarding penetration depth must be considered. This is likely to limit the applicability of inkjet printing to higher frequencies.

Metallized nonwoven fabrics

Nonwoven electrotextiles are a largely untouched area of research as a manufacturing method for wearable antennas. In textile technology, nonwoven technology is assigned

to the field of surface production. Nonwovens differ from classical materials (woven, knitted) primarily in the fact that they are manufactured without the process step of yarn production. Here, the textile surface formation takes place directly from the plastic or fiber without any detours. As a rule, nonwovens have a tangled fiber layer and thus tend to have isotropic material behavior, whereas woven fabrics have an anisotropic structure due to the defined warp and weft thread direction (Pietsch, 2011).

One of the future goals in the field of textile-based antennas is to produce compliant antenna designs with clean and sharp edges/corners and to develop antennas with a conductive surface volume similar to their metal counterparts (Wang et al., 2015). Electrospun nonwoven fiber matrices yield a continuous conductive material with a coverage factor similar to metallic antennas because conductive chain-oriented nanofibers create a continuous conductive path on the surface. This technology can be used to develop complicated antenna designs with high resolution and precise geometry. Electrospun nonwovens have a higher surface volume fraction than nets produced by knitting, weaving and embroidery. A multi-threaded structure with a large surface area is created, resulting in high conductivity comparable to copper.

Furthermore, the use of nonwovens allows for larger antennas at significantly lower weight and cost (Deaett et al., 2008). However, it should be kept in mind that metallized nonwovens exhibit lower flexibility and elasticity, making them less suitable for applications that require high stretchability. In contrast, knit and woven fabrics tend to be more resilient and elastic, making them more suitable for applications such as sportswear and medical devices.

Characterization of conductive materials

If the focus is on the textile patch antennas mentioned in the introduction, the conductive material for the patch and ground plane plays an important role in addition to the thickness and dielectric constant of the substrate. To ensure good performance of the antenna, textiles are selected based on their electrical and mechanical properties. Three forms can be found in the literature: metallized polymer yarns (Breckenfelder, 2013; Altaş et al., 2020), conductive hybrid yarns (Safarova & Militký, 2012; Shahzad et al., 2019; Berglin et al., 2012) or conductive polymer threads (Steinmann et al. 2014; Gehrke et al. 2019; Hu et al., 2022; Grancarić et al. 2018). Not only the electrical properties of the yarn, but also the expected service life play a role in the characterization. An additional protective layer is designed to prevent environmental influences, including water, from having a negative impact on the electrical properties of conductive yarns and reduce their service life (Baribina et al., 2018; Periyasamy et al., 2022).

Due to the planar structure of e-textile antennas, the surface resistance and the resistivity ($\Omega \cdot m$) characterize the electrical behavior. A low and stable electrical surface resistance is required to minimize electrical losses and thus increase the efficiency of the antenna. Conductive textiles with a surface electrical resistance of less than 1 Ω/square can be found on the market. At this point, it should be noted that surface resistance is only used to represent materials with a uniform thickness. For conductive threads, linear resistance is often specified, which is measured in ohms per unit length (Ω/m).

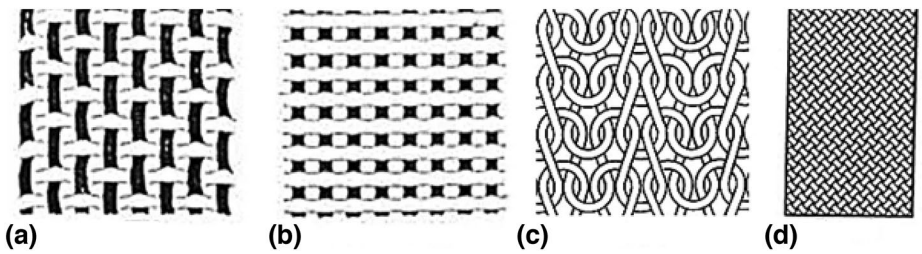


Fig. 2 Classification of fabric structure: **a** Woven fabric structure, **b** Non-woven, **c** Knit fabric structure and **d** Braid (Sobuj, 2015)

Looking at Fig. 2, it quickly becomes clear that also the structure of the material has an influence on the surface resistance. For example, the conductive threads of the fabric on the left side can be better aligned with the direction of the current, making woven structures more efficient due to the low conduction losses.

The surface resistivity ρ_s is related to the conductivity via the following equation. Here, t describes the thickness of the material:

$$\sigma = \frac{1}{\rho_s \cdot t} \qquad \left[\mathrm{Sm}^{-1}\right]. \tag{1}$$

In order to be able to establish textile antennas on the market and to use them purposefully in sectors like medicine, sports or the military, factors such as washability or drying must be taken into account in addition to the electrical properties (Lam et al., 2022). Rotzler & Schneider-Ramelow (2021) discuss the influence of various variables on the washability of e-textiles. Among other things, the influence of conductive yarns and textiles is presented. According to this, conductive yarns mostly show a low resistance to washing and drying processes.

In contrast, manufacturers such as CleverTex (Hrdinova & Hanik, 2010) or Amann (AMANN group, n.d.) advertise products that have excellent washing resistance and are also suitable for industrial washing. They rely on hybrid conductive threads, which allow flat passive elements such as antennas to be integrated directly into textiles. Threads coated by conductive materials or threads containing conductive wires serve as the basic building block and enable wash-resistant, flexible and stretchable units. Therefore, the structure and the most important properties will be discussed in more detail in the next subsection.

Conductive hybrid threads

The technology for producing electrically conductive hybrid threads makes it possible to combine ultra-fine metal wires based on stainless steel, copper, brass, nickel or iron alloys with synthetic threads such as polyester (PES) or polyamide (PA). CleverTex (Hrdinova & Hanik, 2010), for example, twists metallic microwires with a non-conductive textile material, usually a high-strength PES thread (Fig. 3). A multifunctional smart yarn is the result of this process. It is fully compatible with known textile technology processes such as sewing, embroidery, weaving or knitting.

If we look at possible thread types in Table 2, remarkable electrical properties become apparent. Comparing the individual lines with each other, they differ mainly in the

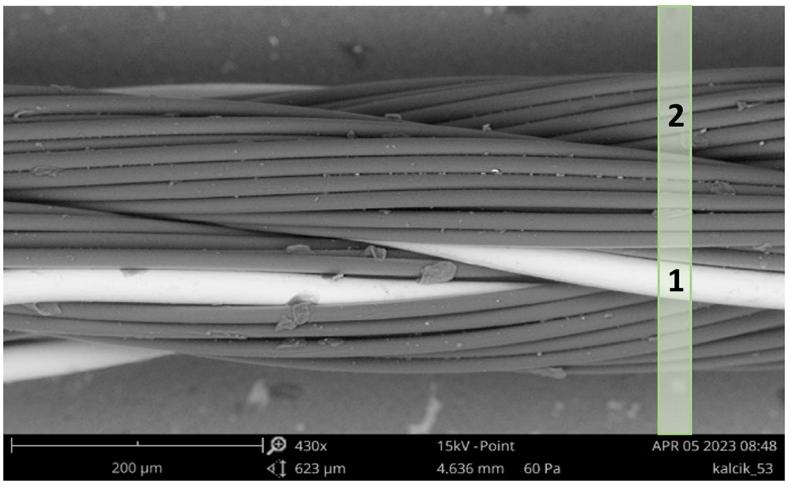


Fig. 3 Multiple twisting of metallic microwires (**1**) with a non-conductive textile material like cotton, polyester, etc. (**2**)

Table 2 Overview of the most important material parameters of different hybrid conductive yarns

#	Material composition	No. of synthetic threads	No. of metal wires	Optical diameter [mm]	Fineness [tex]	Linear resistance [Ω/m] (nominal value @ 20°C)	Tenacity [cN/tex] (textile strength)
1	PES multifil/Cu Ag	4	4	0.23	51	6.5	31.6
2	PES multifil/Cu Ag (insulated)	4	4	0.23	51	6.5	32.0
3	PES multifil/Cu Ag	2	8	0.16	65	3.0	14.0
4	PES multifil/Cu Ag (insulated)	2	8	0.18	68	3.0	13.5
5	Elastil multifil/Cu Ag	2	8	0.21	70	3.20	7.9
6	Elastil multifil/Cu Ag (insulated)	2	8	0.21	70	3.20	7.9
7	Silver coated Polyamide/Polyester Ticket no. 30	1	2	0.40	96	< 85	30.2
8	Silver coated Polyamide/Polyester Ticket no. 50	1	2	0.36	62	< 150	31.1
9	Silver coated Polyamide/Polyester Ticket no. 120	2	1	0.23	28	< 530	45.0

Optical diameter, linear resistance values represent the average value, i.e. currently measured value can be in the range ± 5 %

number of conductive wires in the thread and the diameter. Depending on the area of application, there are also differences in the use of the conductive material. All these factors influence the electrical properties—mainly the electrical linear resistance, which is generally very low when using conductive hybrid threads.

The following list shows further properties and advantages of conductive hybrid yarns, which are listed on the manufacturers' websites (Hrdinova & Hanik 2010; AMANN group, n.d.).

- Non-toxic, no skin irritation;
- Surface of the monofilament can be selected as either an insulating or electrically conductive variant;
- High mechanical resistance; and
- Resistance to maintenance stress.

Possible material suggestions for defined application area

The overall goal of the next area of research is to develop prototype textile antenna-based sensors that can be integrated into garments and sleeves and allow long-term monitoring of the state of oedema and its development during the day. Based on the defined field of application ("Project-specific application and challenges" section), initial suggestions will therefore be made at this point regarding possible threads that can be knitted into a garment.

According to CleverTex (Hrdinova & Hanik, 2010), threads based on silver-plated copper wires are particularly suitable. Two variants are available in each case:

- non-insulated wires (so-called bare wires); and
- wires insulated with a thermoset PUR insulation

If the end product is in a direct connection with the skin, insulated wires are usually preferred. In this way, the skin is not irritated by the metal. However, possible problems with contacting or de-insulating the wires for electrical contacting should be considered. The insulation of textile wires is still under development. Various materials, in particular thermoplastics, are currently being investigated. However, the wire insulation does not affect the mechanical or electrical properties (Table 2) of the finished filaments.

As can be seen from Table 2, PES has often been used in the choice of synthetic filaments. Elastil is also a modified PES, which has higher elasticity and is suitable for knitwear.

The developed antenna-based sensors for textiles should have high mechanical resistance and minimal degradation of textile performance. Clevertex recommends choosing the thread that expands a higher number of individual wires. If several wires break, the multi-wire thread can still work.

The Amann Group product line, on the other hand, contains three products made of silver-coated polyamide/polyester hybrid. Table 2 again summarizes the most important properties, as found in the manufacturer's data sheets (AMANN group, n.d.). The multifilament, silver-coated yarn is 3-ply twisted. AMANN Silver-tech 30 and AMANN Silver-tech 50 both consist of two branches of silver-coated polyamide and one branch of polyester. AMANN Silver-tech 120, on the other hand, has one branch of silver-coated polyamide and two branches of polyester.

Possible antenna topology for defined application area

From an antenna performance point of view, stable antenna characteristics and maximum radiation efficiency are desired, which requires that the effects of human body proximity be minimized. The latter also means that morphology and body movements should not significantly alter the antenna's operating characteristics.

As described in the introduction, textile antennas for data transmission as well as antenna-based sensors will be developed in the future course of the project. The use of antennas as sensors (e.g., monitoring respiratory rate or long-term monitoring of oedema status) requires that they be placed in close proximity to the human body. The textile-based microstrip patch antenna provides sufficient shielding from the human body thanks to the adequately large ground plane, so that the radiation characteristics of the antenna hardly change in the vicinity of the human body. As the antenna radiation is diverted away from the human body, the absorption of EM fields in the body tissue can be reduced (Mahfuz et al., 2022).

The majority of published studies on high-frequency conductive textiles so far deal with computer-controlled embroidery, where conductive elements, such as a patch, are embroidered on a non-conductive textile base or substrate layer (Seager et al., 2013). Knitted textiles for technical and medical applications have also been addressed in the literature (Bettermann et al., 2023; Fan et al., 2020). Looking more closely at knitted structures, a regular arrangement of the unit cell is characteristic. These are periodic arrangements whose wavelength is comparable to or smaller than the structure's period. Resonance phenomena are expected to be due to the natural periodic structure of the knitted fabric. Currently, there are no known publications that critically address either this aspect or high-frequency characterization of knitted conductive structures in general, particularly in the millimeter frequency range (30 GHz to 300 GHz).

Primarily, the published works are purely metrological recordings of reflection and transmission coefficient (Tennant et al., 2012; Williams et al., 2007)—mainly for the improvement of EM shielding (Tunakova et al., 2020). Since EM simulations of knitted structures have not been systematically investigated so far, there is no quantitative evaluation regarding the effect of deformation on EM parameters such as surface current distribution, field distribution, etc. A simulation and the additional knowledge regarding the periodic material structure should lead to insights that cannot be obtained by a purely metrological analysis. The theoretical models to be developed will deepen the knowledge of the periodic structures and reduce the corresponding analysis on the real structure remarkably.

Feeding techniques for patch antennas

Due to the flexible structure of a textile antenna, factors such as bending, stretching and moisture must be taken into account, which makes the performance to be highly sensitive and volatile. An essential step in providing stable antenna operation is the selection of the most appropriate feedline technology, as the key to an efficiently operating textile antenna is to ensure maximum power transmission.

The majority of newly developed flexible textile antennas have a coaxial feed mechanism to test the performance. Nevertheless, flexible antennas proposed in literature are

now more often based on planar feeding techniques. In general, the contacting options used can either have a direct connection, including microstrip inserts and coplanar waveguides (CPW). Alternatively, indirect feeding mechanisms, such as capacitive proximity feeding or aperture coupling, have also been proposed. A summary of different techniques and their advantages and disadvantages for textile applications can be found in Table 3, although a first overview is already given in the further course.

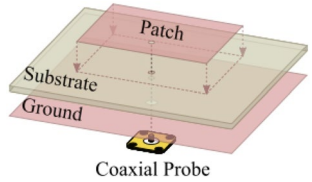
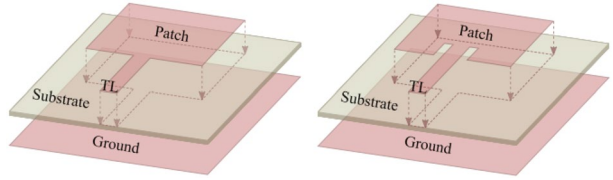
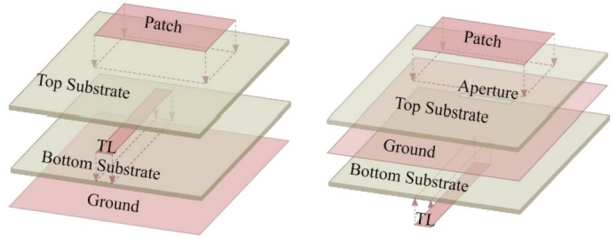
The coaxial feed technique has the outer conductor of the coaxial probe connected to the ground plane, and the inner conductor penetrates the dielectric and makes contact with the patch. The coaxial probe introduces an inductance that depends on its length and is determined by the substrate thickness of the antenna (Xu et al., 2005; Sankaralingam & Gupta, 2010). The main advantage of this technique is that the coaxial feed can be placed anywhere within the patch to match the 50Ω input impedance. Thus, it is easier to find the correct impedance point than with the transmission line technique. Impedance matching is easily achieved using capacitively coupling radiators (Samal et al., 2014) or by adjusting the position of the feed point (Van Baelen et al., 2018; Sankaralingam & Gupta, 2010). In addition, the ground plane isolates the spurious radiation from the feed and results in better radiation performance (Pazil et al., 2021). Since flexible textile antennas are ergonomically more suitable for on-body operation, this feeding technique is not ideal. The rigid coaxial probe is part of the antenna and cannot be removed after the antenna test, so we focus on planar solutions for wearable applications in the remainder of this paper.

Microstrip feeding is often used as a planar option in textile technology. In addition to a radiator patch, the dielectric substrate and a ground plane, a transmission line (TL) is also required, as shown in column 2 of Table 3. With this feeding technique, the input impedance of 50Ω can be obtained by modifying the length and width of the TL. However, microstrip feeding is suitable only for thin substrates, since the 50Ω microstrip line otherwise becomes very wide. Excitation of higher order modes follows as a consequence (Pazil et al., 2021). Undesired cross-polarization radiation also degrades efficiency and bandwidth performance. If we consider inset feeding in parallel, problems can arise here during fabrication with regard to the tolerances of textile technology, since the slots on both sides of the feed line must be very narrow in order to achieve a characteristic impedance (Joler & Mihalić, 2022). For this reason, the proximity feeding technique will be investigated next.

Ideally, multilayer feeding techniques provide better textile performance than, for example, coaxial probes, since there is no need for rigid pins going through different layers and the connector can be removed after the antenna is evaluated. Multilayer microstrip feed techniques increase antenna bandwidth (BW) and are robust to bending. However, due to the multilayer alignment, a very precise fabrication process is required (Grilo & Correra, 2015).

Basically, there are two main techniques of multilayer feeding. The first type is called EM coupling scheme or proximity coupled feeding technique. In this technique, two dielectric substrates are used so that the feed line is located between the two substrates and the radiating area is located on the top substrate. The proximity feeding mechanism has the distinct advantage that any radiation is shielded from the feed line and potentially re-radiated from the patch, resulting in good cross-polarization and body isolation

Table 3 Comparison of various feeding mechanism in the literature and their advantages and disadvantages for textile antennas

Reference	Feeding Mechanism	Advantages	Disadvantages	Basic Scheme
Kuang et al. (2018); Sundarsingh et al. (2017)	Coaxial feed	— Simple fabrication — Good compactness in terms of the overall volume — Impedance matching can be easily obtained	— Not ideal for real textile applications that are expected to be flexible and comfortable, since the rigid coaxial probe is part of the antenna and can not be removed after antenna testing	 Del-Rio-Ruiz et al. (2019)
Locher et al. (2006); Wiri (2021); Karimi et al. (2018)	Microstrip line	— Decreases the manufacturing complexity — Improves the antenna's flexibility — Feed can be etched on the same substrate layer to provide a planar structure — Simple to model	— Increase of TL length also increases the losses, the overall size of the antenna, and the impedance matching complexity	 Del-Rio-Ruiz et al. (2019)
Grilo et al. (2016); Grilo & Correra (2015)	Proximity coupling	— Bandwidth increase — Good cross-polarization — Good body isolation	— Depending on capacitive coupling — Stacked configuration can increase the manufacturing cost significantly	 Del-Rio-Ruiz et al. (2019)
Jothilakshmi et al. (2015); Ramkumar et al. (2020)	Aperture coupling	— Bandwidth increase — Reduction in spurious radiation	— Not ideal for off-body communications since the TL is not isolated from the body — Stacked configuration can increase the manufacturing cost significantly	

(Del-Rio-Ruiz et al., 2018; Duffy, 2000). Compared to other feeding methods, the use of a proximity feed can not only improve the operating BW of the antenna (Grilo & Correra, 2015), but also reduce the footprint of the design, making it more suitable for integration into a portable system (Martinez et al., 2020). The coupling between the patch and the microstrip feedline is inherently capacitive - limiting this technique for large substrate thicknesses. If the distance between the feed line and the radiating layer exceeds a critical limit, inefficient capacitive energy transfer occurs due to limited EM coupling, usually resulting in poor impedance matching. However, approaches to counteract this problem can already be found in the literature. It essentially involves a microstrip line with a vertical short to the top metal layer (Pinapati et al., 2020). This should allow the excitation of a wide range of textile antennas—especially interesting for substrate thicknesses that are not practical with traditional methods such as inset feeding and traditional proximity feeding.

An increase in BW by non-contact feeding methods can also be achieved by aperture coupling. In this approach, the radiating patch is separated from the microstrip feed line by the ground plane. The coupling between the patch and the feed line is provided by a slot or opening in the ground plane. To what extent the feedline and patch are coupled is determined by the shape, size, and location of the opening (Ramkumar et al., 2020). In general, interaction between the feedline and the radiating conductor can be avoided using the aperture technique, leading to a reduction in spurious radiation. The main disadvantage is the high back radiation, which is undesirable for body worn communications (Del-Rio-Ruiz et al., 2018). In aperture coupled feed technique the feed line is directly in contact with the tissue and hence absorption is actually larger, which results in a high level of Specific Absorption Rate (SAR) under the antenna (Leduc & Zhadobov, 2017).

Contacting options for electronic textiles

The possibility to connect electronic components or electronic modules with fabric circuits is of significant importance for applications in the field of e-textiles. In the following, different approaches with regard to contacting will be presented and their advantages and disadvantages listed. Basically, a distinction is made between connectors and permanent connections.

Snap fasteners

Connectors are often associated with the concept of modularization. A major concern regarding electronics in textiles is reliability during washing. In Belov et al. (2008), a robust, interchangeable snap-on electrical and mechanical connection is used that allows components to be removed before washing. In the literature, common snap fasteners from the textile industry are often mentioned (Fig. 4a), which are sufficiently reliable both mechanically and electrically (Chen et al., 2016; Linz et al., 2005). Different application requirements, such as convenient reuse, recycling, or disposal of components are among the main advantages of this technology (Dang et al., 2022). Since textiles mainly have a two-dimensional character, the size of the connectors has a negative impact.

Permanent connections are particularly useful when using conventional SMD components. A large number of applications are already known for the development of intelligent textiles in the fitness or health sector. Again, factors such as washability, elasticity or wearing comfort play a role in the choice of contacting options.

Contacting by ultrasonic welding

Welding is a process used to join both metals and textiles, and in both cases the materials to be joined are melted locally. The fundamental difference between the welding and soldering method is that an additional material is not melted to make the joint, but the materials themselves melt. Welding is not a common joining technique for e-textiles, however there are certain applications for which it shows great benefit.

First, the ultrasonic welding process is presented, which is a way to replace the much larger snap fasteners. The joining process is based on a combination of ultrasonic vibrations and pressure, whereby thermoplastic material is melted in the welding area and penetrates into the fiber interstices. Subsequent solidification takes place under pressure. This creates a mechanical and electrical joint in the same process. The welding results are influenced by various parameters and effects. For example, the strength of the welded joint depends on the amount of molten material at the welding point. The addition of another thermoplastic material in the weld area can significantly improve the reliability and durability of the realized joints. Furthermore, factors such as the type of processing (woven, knitted, non-woven) or the right choice of welding tool play a role. It is characterized as an established, economical and fast process, which is easy to automate and well suited for mass production in the textile industry (Jones, 2013).

This joining process is frequently found in the literature: for example, in Micus et al. (2021) a method is presented to connect wires for cable-based applications to the functional textiles by ultrasonic welding. The authors in Dils et al. (2022) focused on the realization of stable, low-impedance electrical contacts between crossing hybrid conductive yarns by ultrasonic spot welding (Fig. 4b). Atalay et al. (2019) implemented ultrasonic welding technology to analyze its suitability for the production of e-textile transmission lines. Two groups of yarns, namely stainless steel yarns and silver-plated yarns, were investigated together with PES fabrics.

In the course of these experiments (Micus et al., 2021; Atalay et al., 2019; Dils et al., 2022) some results appeared, which are to be considered depending on the application. Contact resistance is one of the crucial quantities in the analysis of electrical contacts. Four-wire resistance testing is particularly well suited for determining contact resistance without taking the lead resistance of the test wires into account. The measurement of contact resistance can provide information about the quality of the contact itself. The resistance increases during the washing cycles as the coating of the conductive yarns suffers from the mechanical and chemical stress during the washing process. While the first few cycles did not have much effect on the measurement results, after repeated washing and drying cycles, a decrease in conductivity and an exponential increase in resistance could be perceived. Comparing different papers, it can be seen that this also depends on the selected yarn and its composition (Atalay et al., 2019). In addition, it was shown that the compounds were hardly affected mechanically by the washing process. The results of the washing cycles prove that machine washing has no influence on the adhesion

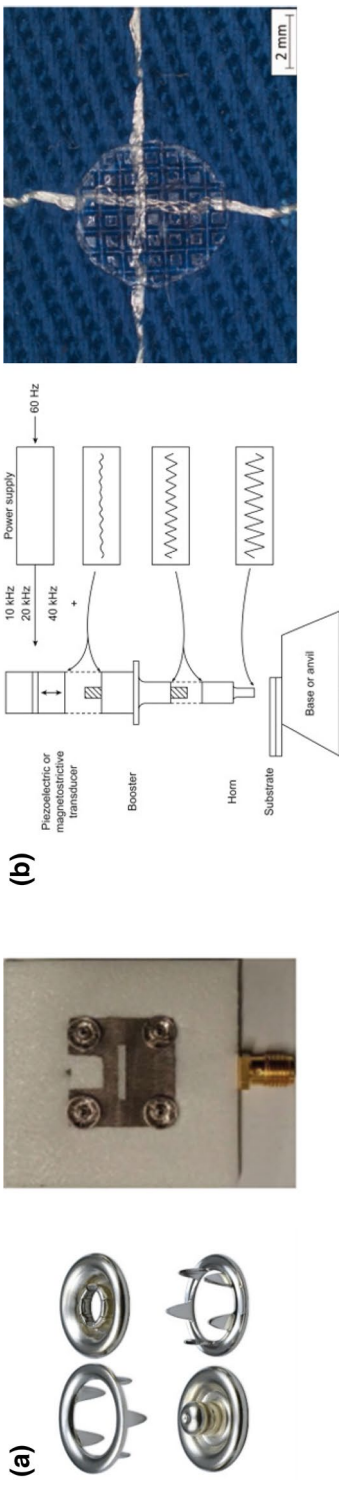


Fig. 4 Practical realization of different contacting options: **a** A modular antenna design utilizing commercial snap-on buttons as mechanical and electrical (RF) connectors (© [2016] IEEE. Reprinted, with permission, from Chen et al. (2016)), **b** Ultrasonic welding machine structure and microscopic images of the crossing of conductive hybrid yarns after ultrasonic welding (© [2015] Reprinted from Petrie (2015), with permission from Elsevier, Dils et al. (2022))

strength. Contacting by ultrasonic welding enables a safe and reliable bonding. Since the method refers to wearable technologies, parameters and materials must be chosen carefully to avoid damage to the conductive fabric (burns, breaking of conductors). Furthermore, it is known that the mechanical resistance and long-term stability of the ultrasonic welded electrical connection can be further strengthened by a non-conductive adhesive (TPU) or a conductive insert (Ag-coated nonwoven).

Contacting by resistance welding

Resistance welding has proven to be one of the most effective ways to make cross-point connections and disconnects. Dhawan et al., (2004) published findings obtained in the fabrication of electrical circuits from woven fabrics. A number of possible methods for making interconnections and disconnections at crossing points in woven circuits required for signal transmission were investigated by them. They focused on two types of resistance welding techniques, namely top-bottom welding and parallel gap welding (Fig. 5).

In general, resistance welding generates heat at the interface of the components being joined by passing an electric current through them. To form the welding seam, the current is applied for a certain period of time while an appropriate force is exerted at the intersection of the components (Post et al., 2000).

As mentioned above, in top-bottom resistance welding, the welding current is applied at the intersection from an upper probe and flows across the plane of the fabric to a lower probe, heating and melting the conductive filaments at the intersection. In parallel gap welding, the welding current is applied from one side of the fabric using two parallel welding probes. The welding current flows from one of the welding probes to the orthogonal conductive filaments at the crossing point and then to the other welding probe. The method of parallel gap resistance welding is particularly useful when fabric-based circuit boards need to be separated at certain points to control the current path in the circuitry. By using a high welding current, a great amount of heat can be generated which melts the thread material between the probes, causing cuts or interruptions.

To determine the mechanical and chemical resistance of the welded joints, many tests have already been carried out in the literature. In general, Dhawan et al. (2004) indicates minimal peripheral damage to the adjacent PES fibers due to welding. The damage becomes greater as the value of the welding current increases during top-bottom welding. In summary, top-bottom resistance welding provides less favorable results than parallel-probe resistance welding in this regard. Suchý et al. (2020) published results after dry heat test, bending test, thermal shock test and washing test. The results show that the welding seams are resistant to increased temperatures. Also, the bending test did not show any significant changes in the electrical resistance of the produced welded joints. Major problems could be detected in the washing test, since resistance welding in the contact area removes the non-conductive components in the thread structure. As these provide the mechanical strength to the thread, a high number of failures could be observed with increased load due to washing. Resistance spot welding requires that the contact area be coated with additional material after welding. This process is a major disadvantage of resistance welding, making it more time-consuming compared to ultrasonic welding.

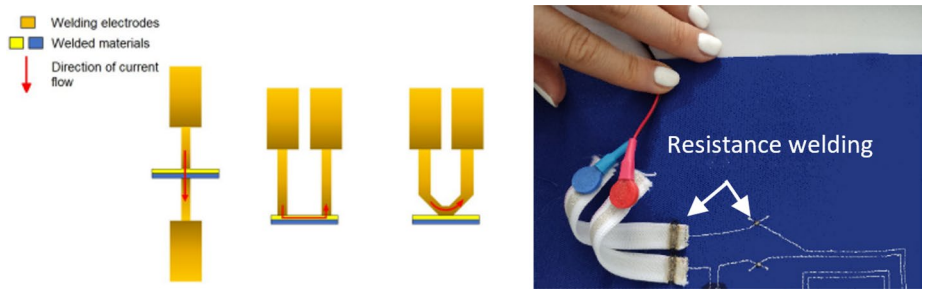


Fig. 5 Three basic methods of resistance welding and an example of realized contacts (© [2022] IEEE. Reprinted, with permission, from Suchý et al. (2022))

Contacting by thermocompression bonding

The processes presented above or in the literature, such as ultrasonic welding or embroidery (Linz et al., 2005; Stanley et al., 2022), were developed specifically for textile substrates and have a low contact resistance. However, it is necessary to increase the mechanical and chemical resistance, which is only possible through an additional step in the manufacturing process—encapsulation.

The combination of pressure and heat for welding is called thermocompression bonding (Mehmann et al., 2017). This is another way of contacting SMD components and electrical modules. It is an inexpensive and easy to realize solution, mainly used in smaller quantities or for individual layouts (Fig. 6).

For this connection technique, the first step is to design a component housing with cavities, which is then produced using a 3D printer. The components can be fixed in it without the use of an additional bonding agent. Again, in its simplest form, this is a purely mechanical contact. The SMD component is pressed onto the conductive layout and fixed in place by the housing, which is then melted onto the textile substrate and cooled under continuous pressure. The same process can be repeated on the reverse side of the textile to protect the electrical contact area on both surfaces. The three variables of this process - temperature, time and pressure - can be customized. Thus, encapsulation is carried out together with the electrical contact in a single production step.

Again, the scope of application has already been limited by various functional tests using four-wire resistance measurement. The authors in Hirman et al. (2022) use the thermocompression method with one-sided encapsulation for electrically conductive textile stretchable ribbons. It turns out that this method is not suitable for this type of application and stress. In contrast to contacting with electrically non-conductive adhesive (NCA) in the next paragraph, the electrical resistance increases quickly in this case and the joint did not withstand the functional test in practice. However, promising results were obtained by a more complex thermocompression method in Kalaš et al. (2020). The contact resistance increased only slightly during washing and drying. Furthermore, the electrical contact resistance in Kalaš et al. (2021) could be reduced by applying SnBi solder paste to the conductive textile pads or by realizing SnBi bumps on the SMD component leads.

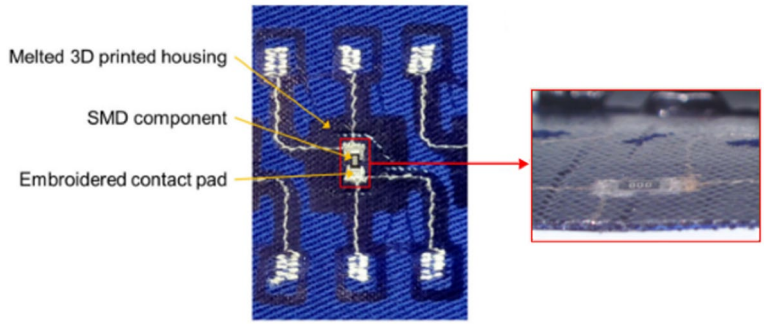


Fig. 6 Detail of contacted resistor fabricated by the thermocompression technique and a side view of the encapsulated SMD component (Kalaš et al., 2023)

Non-conductive adhesive bonding

Finally, a contacting method based on a non-conductive adhesive bonding will be presented, as it is both simple and very versatile in terms of the selection of fabric circuit and the type of electronics to be contacted.

The choice of adhesive depends on the particular application. In Hirman et al. (2022), a UV-curable, acrylic-based adhesive AA3926 from Henkel Company is proposed. It is beneficial that the adhesive cures and does not re-melt when the assembly is exposed to high application temperatures and also a high modulus can be observed. Both could improve the reliability of the contact under harsh environmental conditions.

Since textiles are subjected to dynamic loads such as bending or stretching, the authors in Linz et al. (2012) rely on thermoplastic elastomer adhesive with low modulus. Contacts based on thermoplastic adhesive are potentially repairable as they can be re-melted. Since insulation of conductors is important in many textile electronics applications, the authors show that there are advantages if the adhesive for the bonding process is identical to the thermoplastic insulating material of the textile circuit. The problems that can arise when thermoplastic elastomers are used as adhesives are contact degradation due to temperature-induced movement of the components and increased stress relaxation of the polymer.

Generally, direct contact between the conductive filaments and the component pad is made by mechanical pressure alone. The adhesive is only used to fix the mechanical contact.

Apart from their good conductivity, the adhesive-bonded contacts proved to be very reliable. Several reliability tests have been performed in the literature (Linz et al., 2012; Hirman et al., 2022; Von Krshiwoblozki et al., 2012), where the contact resistance was measured after multiple loading and between several wash cycles using the four-wire method. During these tests, the contact resistance did not increase significantly. Only in the first cycles an increase could be noticed, in the further course of the measurement the values stabilized. The adhesive bonded samples withstood thermal stress and temperature-humidity tests without failure. For this reason, it can be concluded that it is a reliable technology for integrating electronics into textiles. The use of adhesive-bonded connections is advantageous, especially between SMD components and electrically conductive, stretchable textile ribbons (Fig. 7).

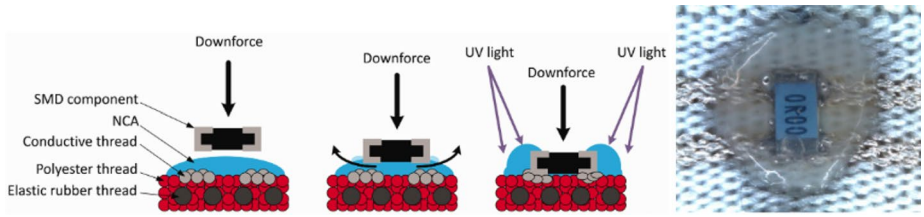


Fig. 7 Principle of non-conductive adhesive technology using the example of the connected component on a ribbon (© [2022] by Hirman et al. (2022) Reprinted by Permission of SAGE Publications)

Conclusions

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 microstrip 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, Microstrip 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, Thermocompression Bonding, Non-Conductive Adhesive Bonding) and reversible methods (Snap Fastener).

Abbreviations

BW	Bandwidth
CPW	Coplanar waveguide
EM	Electromagnetic
IoT	Internet of Things
NCA	Non-conductive adhesive
PA	Polyamide
PES	Polyester
RF	Radio Frequency
SAR	Specific Absorption Rate
TL	Transmission line
TPU	Thermoplastic polyurethane
UHF	Ultra high frequency

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Author contributions
VM was responsible for the literature review and writing of the manuscript. RS and MR provided the current state of research regarding the realization and contacting possibilities of textile antennas. SH and TB supervised the project.All authors read and approved the final manuscript.

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Declarations

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Publisher's Note

Verena Marterer VM received a Master of Science degree in Electrical Engineering from the Ostbayerische Technische Hochschule Regensburg in 2022 and has already focused on the simulation of electromagnetic properties of knitted structures during her studies. Within the scope of a cooperative Ph.D. between the University of West Bohemia in Pilsen and Ostbayerische Technische Hochschule in Regensburg, she is now working on the design of theoretical models describing the electromagnetic properties of periodic fabrics.

Michaela Radouchová MR received a masters degree in Commercial electrical engineering at the University of West Bohemia in Pilsen in 2021. Now she is a Ph.D. student with a specialization in Technology of wearable electronics at the same university. Her main research interests are e-textiles, antennas, and technologies for contacting components on rigid and flexible substrates.

Radek Soukup RS received a Ph.D. in Electrical Engineering in 2009 at the University of West Bohemia in the Czech Republic. During his studies, he completed study exchanges at Danish Technical University and Brunel University in London, Siemens VDO, and Continental in Germany. He is currently the head of the Smart textiles group at the University of West Bohemia. He is the author/coauthor of 65 scientific papers, 19 patents or utility models, 42 prototypes or functional samples, and 8 verified technology. Radek Soukup has led 5 international and 6 national, participated in 2 international and 16 national applied research projects.

Susanne Hipp SH received the Diploma in technical physics in 2007 and the Dr.-Ing. degree in electrical engineering in 2015 both from Technical University of Munich (TUM), Munich Germany. From 2007 to 2012, she was a Research Assistant at the Chair of High-Frequency Engineering with TUM. In 2012, she joined the CST AG (now part of the SIMULIA Brand of Dassault Systemes) as Application engineer in Munich, Germany. Since 2020, she has been professor of high-frequency engineering with the Ostbayerische Technische Hochschule Regensburg, Regensburg, Germany. Her current research interests include simulation of (textile) antennas for IoT and beamforming for 5G+ in particular.

Tomáš Blecha TB received master degree in Electronic and Telecommunications at the University of West Bohemia in Pilsen in 2003, Ph.D. degree in Electrical Engineering on the same university in 2007 and assoc. prof. in 2016 also at the University of West Bohemia in Pilsen. His main research interests are in the areas of design and characterization of microwave printed circuit boards and devices, e-textiles, printed electronics, passive and active electronic components.