Compact, Low-Profile and Robust Textile Antennas With Improved Bandwidth for Easy Garment Integration

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ABSTRACT In this paper, a compact and low-profile proximity-fed textile-based antenna with robust performance and improved bandwidth is proposed for body-area network (BAN) applications. The employed proximity-fed antenna differs from traditional wearable antennas in the sense that it not only exhibits improved bandwidth but also a reduced footprint. The proposed antenna also possesses an extreme robustness when subject to structural deformation and human body loading effects. In addition, the impact of the uncertainty in the dielectric constant (a characteristic associated with most textile material systems) is investigated for the first time. Experimental results show that the proposed proximity-fed antenna outperforms wearable antennas that employ more conventional feeding methodologies. The antenna was fabricated using two different flexible textile-based material systems (i.e., one printed and one embroidered). The advantages and disadvantages of each fabrication approach are discussed. The proposed antenna is characterized in free-space and on a human body, yielding robust performance in both cases.

INDEX TERMS Antenna, textile antennas, embroidered, screen printing, wearable application.

I. INTRODUCTION

Research on body-centric communication systems has attracted significant interest worldwide [1]–[6]. The research not only focuses on theoretical studies but more importantly on how to develop a wearable system which can support an unobtrusive continuous connectivity between people and other wireless devices. To support seamless communications in body-area network (BAN) systems, flexible wearable antennas that are capable of enabling high-performance data transfer between on-body devices and off-body nodes (e.g., sensors, cell phones, routers) are highly desired [7]–[13]. Contrary to conventional antennas, the challenges of wearable antenna design include a small form factor, a low weight, and a high degree of flexibility, which are essential for improving a person’s agility, range of movement, and comfort level. To fulfill these requirements, textile materials are considered an ideal candidate for the antenna design [14].

Although textile antennas are very flexible and can be readily integrated into garments, several challenges must be taken into consideration in the design and fabrication processes. First, the permittivity of the textile is vulnerable to changes in humidity, temperature and pressure, leading to a shift in the operating band and also the impedance matching performance. Moreover, manufacturing tolerances of textile-based systems are much looser as compared with conventional printed circuit board (PCB) techniques, leading to a significantly wider range of uncertainty. In addition, due to the fact that wearable antennas are utilized in a complicated near-body environment, their operating frequency and radiation efficiency can be influenced by body loading effects [15]–[20]. To alleviate these constraints, it is critical to develop...
easy-to-fabricate antennas with improved bandwidth while exhibiting high isolation between the antenna and the host body. To date, several wearable antennas with wide bandwidth and high isolation have been reported. However, these antennas are not well suited for garment integration since they employed either probe-feeds [21]–[24] or excitation based on slot coupling [25]. The former feeding method requires a non-planar architecture (i.e., a vertical connection between layers), while the latter technique provides poor isolation between the antenna and the host’s body. In [26], a microstrip feed has been utilized in textile antenna design, but it requires an electrical connection between the layers which makes it difficult to manufacture in practice.

To enhance the bandwidth while achieving a high radiation efficiency, a proximity-fed textile microstrip patch antenna is, for the first time, proposed for wearable applications. Compared with other feeding methods, the adoption of a proximity feed can not only improve the antenna’s operational bandwidth [28]–[30], but also reduce the footprint of the design, making it more suitable for integrating into a wearable system.

In this paper, a proximity-fed textile-based antenna is designed to cover the 2.4 GHz ISM band (2.4 - 2.48 GHz). The design considerations such as the variability in the permittivity and structural deformation are studied. The antenna was prototyped using two different manufacturing technologies, i.e. screen printing and embroidering methods. The performance of both prototypes was investigated when deformation and variation in the permittivity are presented. In addition, the manufacturing processes and considerations for the two textile-based fabrication approaches are detailed.

This paper is organized as follow. Section II briefly describes the proposed proximity-fed antenna design and addresses its advantages over a conventional microstrip antenna counterpart. Section III details the two different textile fabrication processes and related design considerations. Section IV summarizes the simulated and measured results of the two proposed textile antennas. The effects of human body loading on the performance are also investigated in Section IV. A conclusion is finally drawn in Section V.

II. ANTENNA DESIGNS

The configuration of the proposed compact proximity-fed textile antenna is shown in Fig. 1. The antenna consists of a square radiator patch of length $L_p$ placed on top of a thin substrate with a thickness of $h_1$. This substrate is then stacked on the top of a grounded substrate with a thickness of $h_2$. A microstrip feed line with a length of $L_f$ and a width of $w_f$ is printed on the top layer of the bottom substrate. The antenna geometry was optimized using a commercially available full-wave software package (Ansys HFSS).

A. COMPARISON WITH REFERENCE ANTENNA

In this work, the proximity-feed was chosen in order to enhance the impedance bandwidth of the wearable antenna without increasing its thickness. To appreciate this advancement, the simulated S-parameters are compared to those of a conventional microstrip-fed counterpart (i.e., the reference antenna) with a thickness of 4 mm. The same thickness was chosen here for a fair comparison with the proposed antenna. The dimensions of the microstrip antenna were found based on the design formulas reported in [31]. Both antennas were analyzed using the finite element ANSYS HFSS software. The properties of a screen-printed textile/Ag material system were incorporated into the simulation setup as well as the expected variation (i.e., minimum and maximum values) in the material’s dielectric constant. Based on data provided by the vendor, the average relative permittivity ($\varepsilon_r$) of the given textile material is about 1.7, with a range that spans from a minimum value of 1.65 to a maximum value of 1.75 and has a loss tangent of 0.008. The thickness of the printed conducting layer was fixed at around 45 $\mu$m and its conductivity was set to be $1.3 \times 10^6$ S/m.

The overall footprint of the proposed antenna is 53 mm by 53 mm, i.e., $0.43 \lambda_0 \times 0.43 \lambda_0$. In contrast, the reference antenna has a larger footprint of 69 mm by 75.5 mm, i.e., $0.56 \lambda_0 \times 0.61 \lambda_0$. Compared with the reference antenna, the size of the proposed antenna is reduced by about 46% since no extra space is required for accommodating the feed line. Because of the uncertainty of permittivity in practical applications, a parametric study was carried out to investigate the influence of the permittivity. Figure 2 compares the layouts and S-parameters of the proposed proximity-fed antenna with the reference antenna fed directly by a microstrip line. The results indicate that the operating frequency moves to a lower band as the effective permittivity increases from 1.65 to...
1.75. It should be noted that the bandwidth of the proposed antenna is more than 160 MHz, which is much wider than the bandwidth of the reference antenna (which is about 80 MHz in the band of interest). Owing to the improved bandwidth, the proposed antenna can maintain a return loss of over 10 dB when the permittivity is altered. In contrast, the operating band of the reference antenna shifts out of the frequency range of interest (2.4 - 2.48 GHz) when the permittivity is changed.

Fig. 3 and 4 show the simulated realized gain and radiation efficiency, respectively. Similar results as Fig. 2 are observed when the dielectric constant is changed from 1.65 to 1.75. The proposed proximity-fed antenna has a realized gain of over 6.0 dBi in the broadside direction. The peak gain of 6.3 dBi at 2.44 GHz indicates that a high radiation efficiency of approximately 90% is achieved. On the other hand, the reference microstrip antenna has a realized gain of about 4.9 dBi with a radiation efficiency of 77% over the band of interest. By further comparing the simulation results, we also find that the proposed proximity-fed antenna is less susceptible to the expected variations in the permittivity.

Because the proposed antenna is intended for wearable applications, the effects of structural deformation (i.e., bending) in free space at different radii of curvature ($r_a$ [mm]) are studied. The values of the radius were chosen according to the structural properties of a realistic human body, where the arm has the highest curvature ($r_a = 40$ mm) while the...
Fig. 5-7 compares the simulated S-parameters between the proposed antenna and reference antenna with different radii of curvature when the permittivity is varied from 1.65 to 1.75. As observed, the reference antenna experiences an obvious frequency shift (up to 35 MHz) in S11 as the radius of curvature changes. Due to the narrower bandwidth of the reference antenna, this frequency shift makes it unsuitable for wearable applications. For the proposed antenna, however, the performance is much more robust and not subject to the typical degradation due to frequency shift effects. This is primarily due to the proximity-feed method introduced in this design. It should be noted that the beam-width of the pattern of the antenna is slightly increased, and the gain is slightly decreased when the radius is reduced due to the reduction of effective length of the radiating slot of the antenna.

### B. HUMAN-BODY LOADING EFFECTS

The effects of human body loading on the input impedance of the two antennas were investigated and compared in Fig. 8 and Fig. 9. The flat multilayer tissue and cylindrical tissue models are used to mimic the human chest and arm [22], [32], respectively. The properties for each layer are summarized in Table 1. The antennas were placed in close to the tissue at a distance of 2 mm, which is an approximate spacing between the garment and the surface of the body. The results confirm the robust on-body performance of the proposed textile antenna over the traditional microstrip patch antenna.

### III. FABRICATION OF ANTENNAS

In this section, we introduce two different textile manufacturing technologies that were used to fabricate the antenna prototypes. The objective is to provide a comprehensive illustration on how to integrate the textile antenna design into a wearable garment. First, the fabrication processes of the two types of textile-based antenna prototypes are discussed. Then, the performance of both antenna prototypes is compared with a rigid antenna counterpart developed using conventional PCB technology.

#### A. ANTENNA PROTOTYPE: SCREEN-PRINTING FABRICATION

The first manufacturing technology is based on a textile-silver printing fabrication process. This technology features
a unique way of fabricating textile dielectric materials which are flexible, air permeable and act as a superior medium for high-resolution printing, as shown in Fig. 10. Evolon® nonwoven fabric, provided by Freudenberg, was selected since it has a basis weight of 100 gm/m$^2$ and a thickness of approximately 0.24 mm. Moreover, the Evolon® nonwoven fabric consists of bi-component polymeric micro-fibers (30% of polyamide and 70% of polyester), which have a very high surface area and a high fluid absorbency. Thus, the conductive silver particles of the ink can penetrate to some extent into the nonwoven fiber bulk, which improves the adhesion and durability of the ink on the fabric. This penetration is limited to 0.1 mm and, thus, the influence on the properties of the textile material is negligible. The layers of Evolon® nonwoven fabrics can be laminated with thermoplastic polyurethane (TPU) web to acquire the desired thickness of the dielectric materials. The thermoplastic polyurethane is melt blown to produce TPU, which has a softening temperature of 65°C. This layer is used as a porous adhesive.

In the fabrication process, the Evolon nonwoven fabric was used as a printing media due to its high absorbency. These extruded bi-component fibers are bonded by a high-pressure water-jet. The jet pressure splits both polymeric fibers at the interface and creates a characteristic smooth surface with a high surface area (∼2.05 mm$^2$ per mm$^2$ of fabric area) and a wedge-like microstructure. The engineered manufacturing process imparts Evolon® with extraordinary absorbency due to the capillary force of the split micro-fibers. This phenomenon enables the ink particles to penetrate to some extent into the nonwoven fiber bulk which improves the ink adhesion to the surface. The laminated nonwoven substrate was made by heat pressing three layers of Evolon® with a layer of polyurethane (PU) web in between the nonwoven fabric layers at 150°C for 5 minutes, as shown in Fig. 10(a). The thickness of the polyurethane web is approximately 0.057 mm. The final thickness of the laminated nonwoven layer is 0.8 mm, which serves as the top dielectric layer (layer 1) of the proximity-fed patch antenna.

Similarly, the bottom layer (layer 2) was fabricated by a heat-press process where 6 layers of Evolon fabric were laminated with 4 layers of polyurethane webs placed in between them, as shown in Fig. 10(b). The final thickness of layer 2 is approximately 1.6 mm, where the dielectric constant and dielectric loss tangent are 1.7 and 0.008 respectively [33].

Screen printing masks were created according to the dimensions of the designed antennas, whose performance was confirmed by simulations using HFSS. The mask was applied to the top of the screen while the Evolon®-PU laminated dielectric material was placed underneath the screen. DuPont 5064H silver conductor was applied to one end of the mask and squeegeed with uniform pressure to create the conductive patch. Printing of Ag ink was done on bare
textile dielectric materials without using any interface coating or film layer. The conductivity of the screen-printed silver on the dielectric textile was measured by the two-point probe method to be \(1.3 \times 10^6\) S m\(^{-1}\). The process was carried out to print all the conductive parts of the antenna (patch, feed line, and ground). The patch was printed on dielectric layer 1, while the feed line and the ground were printed on the two sides of dielectric layer 2. The printed patterns were oven cured at 120°C for 5 minutes. Finally, the TPU webs were applied on the top, bottom, and in between the two dielectric layers, as shown in Fig. 11. During the heat press process, the TPU web melts and sinks into the fiber-bulk and the ink layer. The permeation of the ink into the fiber bulk and the permeation of TPU web into the ink layer result in mechanical durability while maintaining a flexible property. Our previous work has proven that an antenna fabricated in such a similar process can enhance the durability while maintaining the resonant frequency and radiation efficiency upon bending and over 15 or more cycles of a washing and drying process [34]. Thus, the proposed antenna is well protected from rough handling, rubbing, and abrupt water absorption, while retaining some porosity to allow the porous antenna to remain breathable. An SMA connector with a 50 Ω characteristic impedance was soldered to the feedline and ground conductors using Chipquik SMDSWLTP32 low melt solder. A Dymax 9001-E-V3.5 encapsulate was applied to the edges of the antenna to protect the dielectric from delamination and strengthen the bond between the SMA connector and the textile substrate.

B. ANTENNA PROTOTYPE: EMBROIDERED FABRICATION

In Fig. 12(a), the automated embroidery process for the fabrication of wearable antennas and RF components is depicted. The antenna and microstrip geometries are first optimized for their RF performance using a commercially available software (Ansys HFSS). Then the CAD file of the geometry is imported to Brother™ Embroidery software where the model is digitized, and stitching patterns are generated. The patterns are then transported to the Brother™ embroidery machine for automated embroidery. The machine uses conductive thread made of Cu/Ag50 amalgam with lay length of 2 mm as specified by the vendor. Based on several trials and the machine’s capability, the stitching density was chosen to be 14 threads/mm for optimum conductivity [35], [36]. Furthermore, the stitching pattern with thread direction parallel to the RF current path (90°-fill stitch) was chosen as it exhibited the least loss [35]. Likewise, thread tension was also optimized to achieve the highest accuracy without thread breakage for proper current conduction. Prototyped textile-based transmission lines have demonstrated resilience to mechanical deformations such as bending and twisting [37].

Fig. 12(b) shows the exploded view of the antenna with ground plane obtained by using the above process on two different textile layers. As shown, the antenna/circuits and ground plane are embroidered separately and then glued together. Later, SMA connectors were soldered onto the textile transmission line to enable port excitation.

IV. ANTENNA CHARACTERIZATION

Three antenna prototypes designed to target the 2.4 GHz ISM band were manufactured and characterized, including one screen-printed textile antenna, one embroidered textile antenna and one rigid counterpart based on conventional PCB technology. Because of the difference in permittivity, the PCB prototype has the same geometry but different dimensions than the other two prototypes. Table 2 summarizes the properties of the materials used for the fabricated antenna prototypes.
FIGURE 13. Comparison between the simulated and measurement results (a) $S_{11}$, (b) broadside realized gain, and normalized radiation patterns corresponding to an operating frequency of 2.44 GHz in both the (c) E- and (d) H-planes of the printed textile antenna, the embroidered textile antenna, and the PCB antenna.

A. FREE SPACE PERFORMANCE
The free space performance of the antenna prototypes was first characterized using an Agilent E5071C network analyzer. The simulated and measured results are presented and compared in Fig. 13. The left column corresponds to the printed textile antenna, the middle column corresponds to the embroidered textile antenna, while the right column to the PCB antenna. The comparison between simulation and measurement results for the three prototypes are shown in Fig. 13(a). It is observed that the measured $S_{11}$ of the three antenna prototypes agree reasonably well with the simulations, showing an impedance bandwidth that falls within the targeted frequency band. The embroidered antenna exhibits a reduced bandwidth as compared with the simulation. The narrower bandwidth is mainly due to the reduction of substrate thickness and the inclusion of a stabilizer layer used in the embroidering process. The frequency shift of the counterpart PCB antenna is mainly due to the fabrication and assembly tolerance.

Fig. 13(b) shows the simulated and measured gains of the three antenna prototypes. The printed textile antenna exhibits a maximum gain of 5.5 dBi, which is approximately 0.5 dB lower than the simulation prediction. The embroidered textile antenna has a higher measured gain than the other two
antennas due to a lower conductive loss (vs printed textile antenna) and larger electrical size (vs PCB counterpart). The discrepancy between the simulated and measured results is attributed to the fabrication and measurement tolerances.

The simulated and measured radiation patterns at 2.44 GHz in both the $E$- $(x-z)$ and $H$- $(y-z)$ planes are shown in Fig. 13(c) and 13(d), respectively. As can be observed, very good agreement between the simulated and measured radiation patterns is achieved.

The simulated radiation efficiency of the nonwoven/printed antenna is around 79%, while the embroidered antenna has an improved radiation efficiency up to 98%, due to the lower loss substrate and higher conductivity of the embroidered layer. For brevity, these results are not shown here. Even though the flexible textile antenna implemented using the screen-printing method has a similar performance as the rigid PCB counterpart, it is 40% thinner, lighter and more flexible.

**B. ON-BODY PERFORMANCE**

The performance of the two textile antenna prototypes is also examined when they are subjected to human body loading. The PCB antenna prototype was not investigated here due to its rigid and non-conformal properties. The performance of the textile antennas mounted on different sections of a human body (i.e., chest, upper shoulder, waist, upper arm, and wrist) was studied, as shown in Fig. 14. Fig. 15 displays the simulated $S_{11}$, realized gain and radiation efficiency of the two textile antennas when mounted on different parts of the body. As observed from Fig. 15(a), the printed textile antenna suffers a noticeable degradation in impedance matching, which is caused by the structural deformation when it is placed on the human body. In contrast, the embroidered antenna exhibits a more robust performance over the band of interest when it is placed on different areas of the body. It is seen from Fig. 15(b) that the gain of the embroidered antenna is improved by about 1 dB over the printed counterpart for the mentioned scenarios.

Fig. 15(c) shows the simulated radiation efficiency of the proposed antenna corresponding to the different manufacturing methods. As observed, the printed antenna prototype has a low efficiency of around 70% in the band of interest, which is about 16% lower than the antenna prototype fabricated using the embroidered technology. It is noted that in Fig. 15(b), the realized gain of the antenna when it is placed on shoulder is higher than other cases, which is due to the deformation of the radiation pattern caused by the phantom head.

The antennas were also tested on a genuine human body, as shown in Fig. 16. It can be seen that the measured $S_{11}$ remains almost unchanged when they are placed on the chest, on the shoulder, on the waist, on the upper arm, and on the wrist, demonstrating that the proposed proximity-fed textile antennas are robust to human body loading effects and structural deformation, making them an ideal candidate for wearable applications.
C. TISSUE MODEL SIMULATIONS AND SAR CALCULATIONS

The effects of human body loading on the textile antennas in terms of the SAR was also investigated. A rectangular multi-layer tissue model representative of the chest was employed with a space of 2 mm between the antenna and the tissue model.

As shown in Fig. 17, the screen-printed textile antenna generates a maximum 1g averaged SAR value of about 2.7285 W/kg when 1 W of input power is excited. For the embroidered antenna, however, the maximum 1g averaged SAR value is around 3.364 W/kg. Hence, the maximum input power for the printed and embroidered antenna are 586 mW and 475.6 mW, respectively, in order to comply with the 1.6 W/kg limitation imposed by the FCC [38].

V. CONCLUSION

Two compact low-profile proximity-fed textile antennas were designed, fabricated and experimentally validated for wearable systems. Two fabrication methodologies, one implemented by screen printing and the other by embroidery, were presented and detailed with the advantages and disadvantages of each technique addressed. Compared with a conventional microstrip patch antenna, the proposed proximity-fed textile antennas not only provide an improved bandwidth, but also a more robust performance in terms of impedance matching and radiation characteristics. Wider impedance bandwidths are particularly important for textile-based antennas since this property provides a means of achieving robustness to bending and body loading effects, as well as uncertainties in the material property variability, which can cause an undesirable shift in their operating frequency (a fact that is often overlooked in the wearable antennas literature). Moreover, the simple design of the proximity-fed wearable antennas makes them extremely easy to integrate into garments. In addition, the structure deformation and human body loading effects on antenna performance were studied and compared. Simulated and measured results confirm that the proposed antenna maintains a wide bandwidth and robust performance when deformation and loading effects are present, which makes it extremely attractive for practical implementation into a wearable system.

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