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Screen-Printed Fabric Antennas for Wearable Applications

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ABSTRACT In this paper, two antennas for wearable applications are presented, including the development of new antennas on fabric substrates for communication with in-body and outside the body sensors. The design process for fabrication via screen printing on fabric substrates is outlined using commercially available conductive inks. The effects of non-conductive, paint-based inks as interface layers between conductive elements and fabric substrates of coplanar keyhole fabric antennas is presented along with wash sustainability and its effects on antenna resonance at 5.8 GHz over time. Fabrication of screen-printed radio frequency identification tag antenna includes placement of the tag chip. Accessibility of the tag is assessed by comparing reader data to distance between the reader and the tag at 915 MHz.

INDEX TERMS Wearable antenna, fabric antennas, textile, RFID, screen printing.

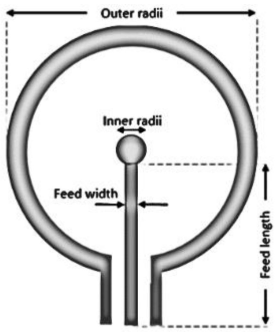
I. INTRODUCTION

THE WEARABLE device industry is growing increasing demand for sensors to be integrated into daily wearables such as clothing and accessories. As of 2019, the wearable device industry accounts for a $28 billion market capitalization and is expected to grow to $74 billion by 2025. So far, some of the most popular wearable technology is in watches, like the Apple Watch and Fitbit. Also, there have are some existing clothing items, like the Myontec MBody smart clothing, where sensors are detachable from athletic apparel including a shirt and shorts. Devices like these tend to be bulky, as the sensors are large and protrude from the clothing item when worn. This prompts the development of more seamless sensor integration as opposed to bulky and obvious sensors.

This paper addresses one way to accomplish this by screen printing conductive inks directly onto the wearable fabric substrate [1]. The first antenna is the coplanar keyhole antenna operating at 5.8 GHz, which is capable of communication with both in body implanted sensors as well as out of body external sensors. The second antenna presented in this paper is an ultra-high frequency (UHF) radio frequency identification (RFID) tag antenna operating at 915 MHz, which can be used for motion tracking applications [2]. Both antennas are simulated in ANSYS HFSS, then tested with skin-mimicking gel to represent the antennas as part of clothing worn against the body. The analysis of each antenna includes pertinent data to its function including transmission between each antenna and the reader with increasing distance between them.

II. SMART WEARABLE FABRIC ANTENNAS FOR COMMUNICATIONS WITH IMPLANTABLE SENSORS

In this section, a novel antenna design manufactured on fabric substrates capable of sensing and communication applications, i.e., with and without implantable sensors, multiple wear usability and machine washable is demonstrated as a wearer can use fabric antenna for communication and/or sensing applications with implanted health monitoring sensors. A new antenna topology capable of unique axis radiation pattern was developed and simulated in ANSYS HFSS electromagnetic simulation suite (see Figure 1) at 5.8 GHz frequency.



Parameter	Measure
Outer radii	1.76cm
Inner radii	0.21cm
Feed length	2.9cm
Feed width	0.4cm

FIGURE 1. **Coplanar Keyhole Antenna design for unique axis radiation.**

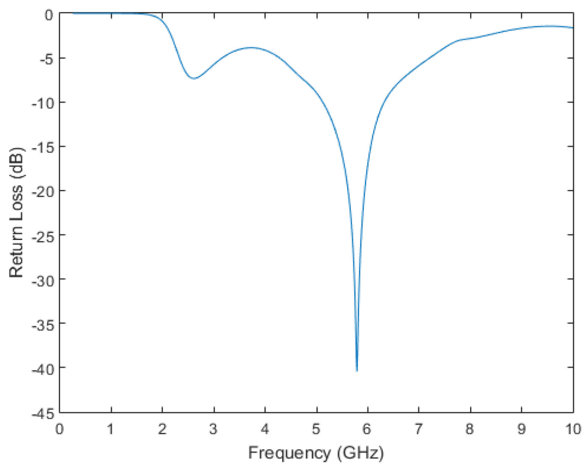


FIGURE 2. **Return loss of simulated coplanar keyhole antenna design in HFSS.**

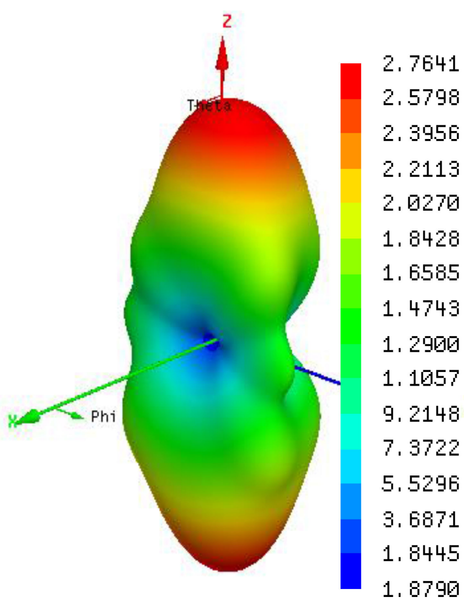


FIGURE 3. **Gain of coplanar keyhole antenna topology at 5.8 GHz.**

The simulated Coplanar Keyhole Antenna (CKA) showed a return loss of −42 dB at 5.8 GHz with 19% bandwidth (see Figure 2).

The antenna was simulated in air, i.e., it was not mounted onto any substrates in simulation settings. As suggested by the design, the radiation pattern was also recorded (see Figure 3).

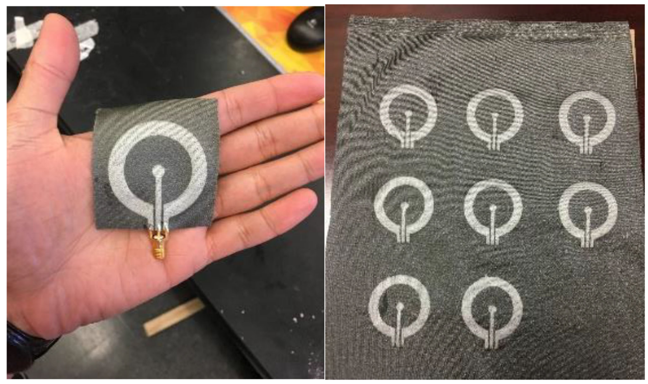


FIGURE 4. **Screen printed CKA on Fabric (Nylon/Spandex) substrate with 3.5mm SMA soldered on.**

As expected, the simulation showed a unique axis radiation pattern, i.e., the antenna showed maximum gain along the positive and negative z-axis only with minimal gain in the x, y-axis.

In order to fabricate the CKA design, screen-printing technology was utilized. Unlike woven or knitted antennas, screen-printed antennas require conductive inks used to create conductive elements of antennas on fabric. Unlike conductive yarn woven antennas, screen-printed antennas provide significantly higher print resolution and lower sheet resolution [3]. It can be used on various fabric types as well. In this study, conductive ink by NovaCentrix (HPS-FG32) was used for antenna fabrication. The conductive ink consisted of silver particles of ∼1.5micron size with $25m\Omega/mm^2$ [4], [5]. screen-printing setup from Ryonet with a 230 mesh screen was utilized to screen-print the antennas on fabric (82% Nylon, 18% Spandex). This particular fabric was selected due to tis high thread count and stretching ability. Before screen-printing, the antenna on-top of a fabric substrate was simulated in HFSS and return loss recorded (see Figure 2).

The fabric material has a relative permittivity of ∼1.5 [6], and during simulation the antenna was mounted directly on to the substrate which subsequently shifted the resonance down by 0.7GHz. This was expected as increasing permittivity of the substrate reduces the resonant frequency. This was countered by scaling the antenna size for 5.8 GHz resonance. Next, the antenna was fabricated using a 230 mesh screen on the fabric substrate and 3.5 mm SMA connecters were soldered on (see Figure). Multiple antennas were screen printed and tested for their return loss (see Figure 4).

The fabricated fabric antennas (CKA) showed coherence in results with resonance at 5.8 GHz. Peak resonance at 5.8 GHz relied heavily on SMA connector soldering technique. Slight changes in SMA connector soldering position effectively shifted the peak resonance significantly. A dual band behavior was also observed at 2.4 GHz and 5.8 GHz for specific antennas however, this can be attributed to fabrication process.

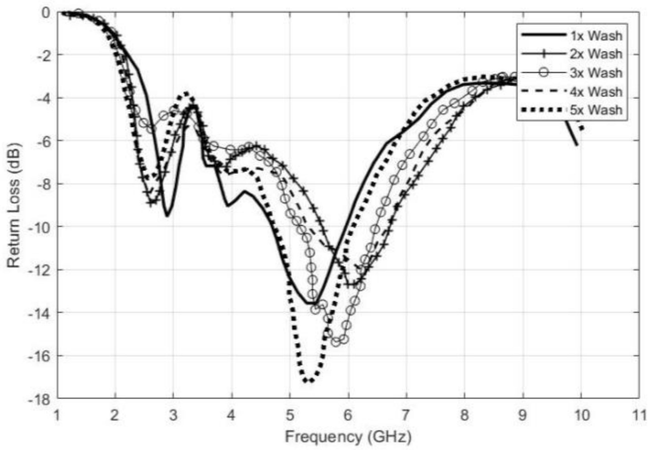


FIGURE 5. Fabric Antenna (CKA) return loss (S11) compared to number of times washed.

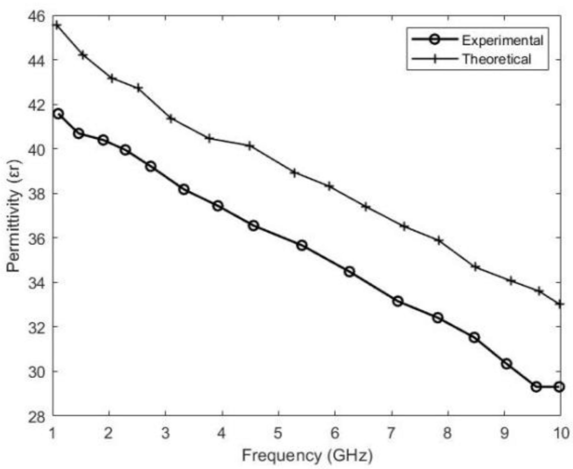


FIGURE 6. Relative permittivity of skin mimicking gel (experimental) compared to actual skin tissue dielectric constant (theoretical) [7], [8].

Since fabric antennas are designed on wearable substrates, they are subjected to similar work-cycle conditions, i.e., prolonged use, subsequent washings and exposure to elements. In order to test viability of the fabric (CKA) antennas, wash tests were conducted. A standard washing machine with 40 degrees Celsius water, 14 rpm for 50 minutes and automatic rinse cycles was used to wash the fabric antennas and test for return loss after each subsequent wash (see Figure 5).

Fabric antennas (CKA) showed resonance at 5.8GHz after five washes opening the door for long term viability and use. Previous shown dual band behavior was also eliminated, this can be attributed to some conductive ink washing off during the first wash cycle.

With the antenna (CKA) fabricated and tested, the next step involved communication with a subcutaneously implanted sensor. Implanted sensors require data transmission capabilities which are achieved either via high gain biocompatible antennas or high-power antenna transmission through the body. Neither approach provides practical implantation as human tissue is lossy while high broadcast power antenna effects within the human body are unknown [7]. Therefore, an intermediary communication antenna, fabric antenna in this case, is needed to mitigate such concerns.

FIGURE 7. Experimental set up for implantable sensor communication with fabric antenna (CKA).

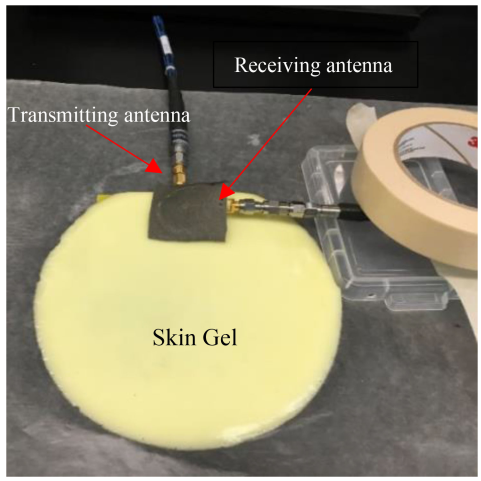


FIGURE 8. Transmitting antenna implanted in skin gel with receiving fabric antenna (CKA) – experimental setup.

The experimental set-up involved a transmitting antenna encased in tissue mimicking skin gel (see Figure 6). This gel mimicking the electrical properties of human skin [7], [8] effectively replacing the need for a live test subject (see Figure 7).

One antenna (transmitting) was encased in skin mimicking gel with 4 mm thickness, coherent to actual human skin thickness, while the second antenna (receiving) was placed 15 mm away from the transmitting antenna simulating a user wearing the fabric antenna with an implanted sensor (see Figure 8).

The transmission (S12) data was recorded using a Keysight network analyzer between 1 and 10 GHz (see Figure 9). Obtained data suggests significant communication capability of the fabric antenna with implantable sensors with up to −30 dB at 5.8 GHz of transmission through lossy skin mimicking gel to the fabric antenna (CKA).

As seen in the SEM images, when screen printing using conductive ink, the silver (Ag) particles tend to sink into the fabric, i.e., the ink bleads into the fabric (see Figure 10). This aspect can be avoided by washing the antenna once, before use, or by introducing an interface layer between the fabric substrate and conductive parts [9] (see Figure 11).

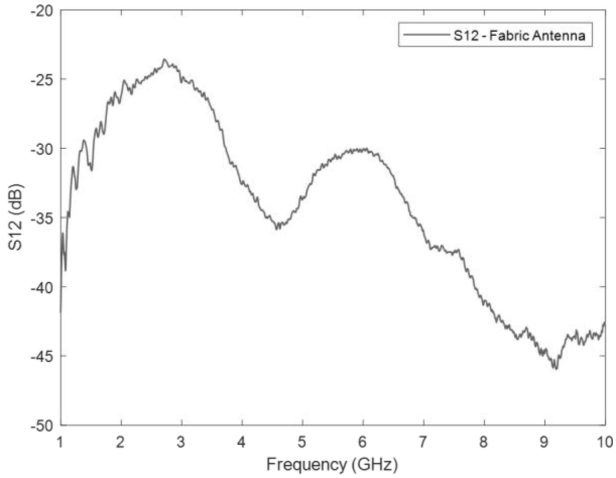
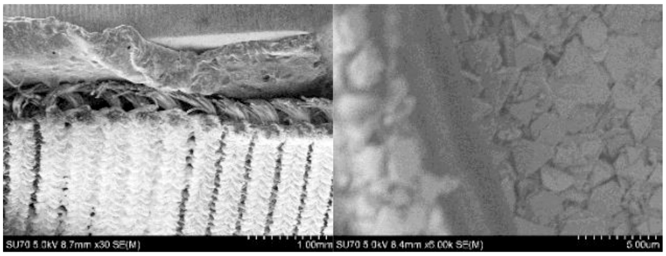


FIGURE 9. Transmission between subcutaneously implanted antenna in skin mimicking gel and fabric (CKA) antenna.



(a) (b)

FIGURE 10. Scanning electron microscope images. (a) Conductive ink on fabric (side-view) 1 mm resolution. (b) Silver particles from conductive ink embedded deep into fabric fibers.

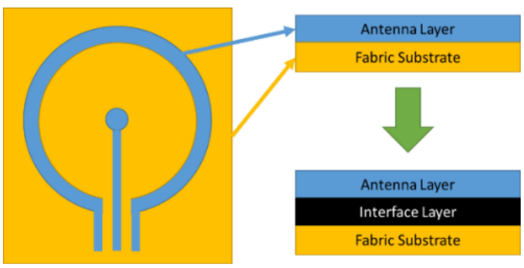


FIGURE 11. Fabric antenna (CKA) with interface layer between fabric and conductive antenna layer.

In order to fabricate the proposed antenna, a commercially available screen-printing ink [5] was used. First, the dielectric constant of the ink was measured using a Keysight network analyzer (see Figure 12).

According to data obtained, the dielectric constant of the ink is 38 at 2.4 GHz. This directly affected the resonant frequency therefore the antenna size was reduced to compensate. However, the reduced size of the antenna deemed it impractical for fabrication as a compatible feed connecter was not available (see Figure 13).

To counter this, the antenna size was scaled up by reducing the resonant frequency from 5.8 GHz to 2.4 GHz. The fabric antenna (CKA) with interface layer was simulated in HFSS and return loss (S11) recorded (see Figures 14 and 15).

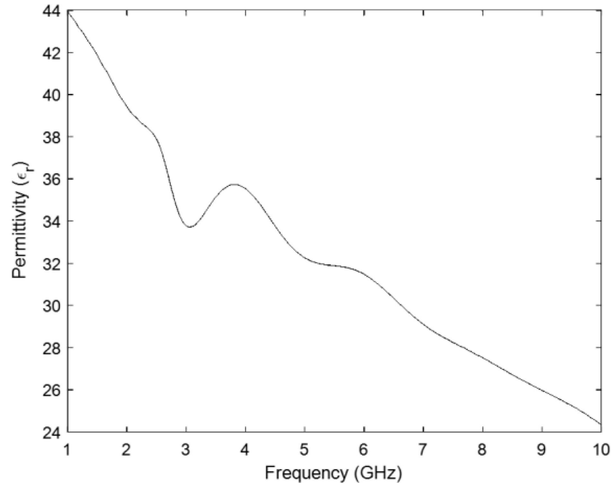


FIGURE 12. Dielectric constant of commercially available screen-printing ink.

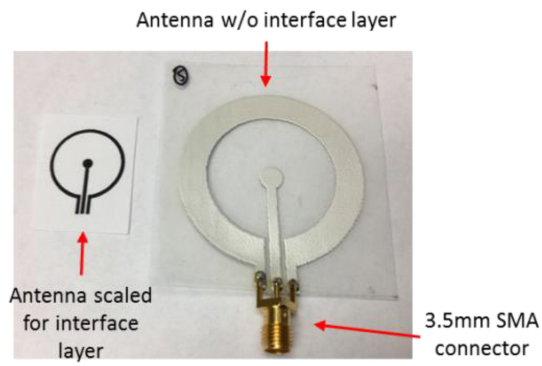


FIGURE 13. Fabric Antenna (CKA) W/O interface layer compared to antenna scaled for interface layer.

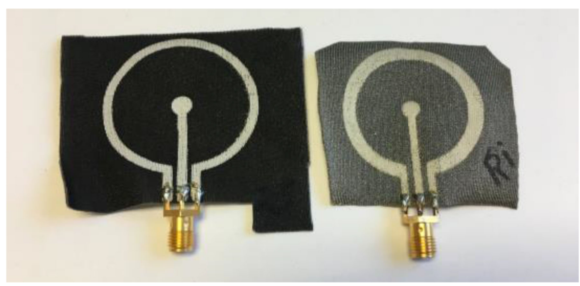


FIGURE 14. (Left) Fabric antenna (CKA) W/ interface layer. (Right) Fabric antenna (CKA) W/O interface layer.

A shift of 0.3 GHz in resonance was observed however, this is attributed to the layer thickness of the interface layer; approximately 100microns. This resonance shift is avoided by scaling the antenna dimensions or by increasing layer thickness of the interface layer however, increasing the layer thickness reduces flexibility of the fabric antenna.

These antennas were also subject to washing to test long term practical viability and operation (see Figure 16).

According to data obtained, observed resonance shift was reduced to 0.1 GHz after washing compared to 0.3 GHz before washing. This is attributed to the conductive particles washed off from the fabric substrates. To further examine

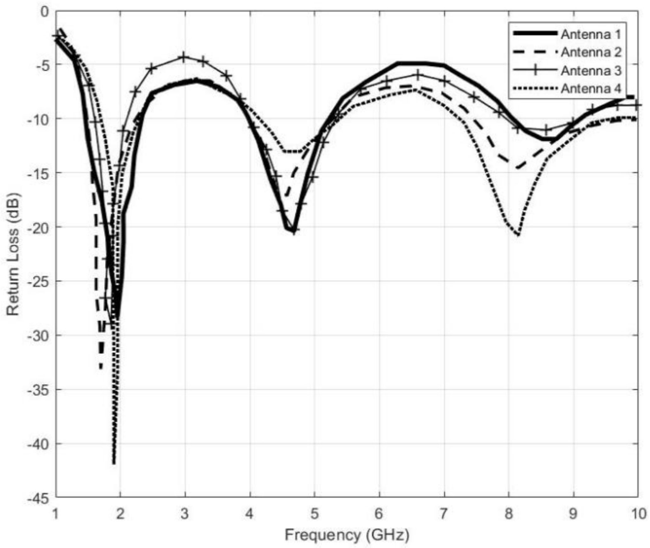


FIGURE 15. Return loss (S11) of multiple fabric antennas (CKA) W/ interface layer.

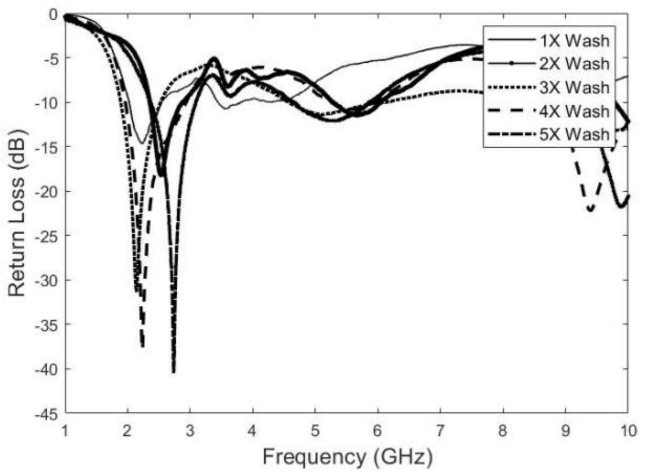


FIGURE 16. Fabric Antenna (CKA) with interface layer return loss (S11) compared to number of times washed.

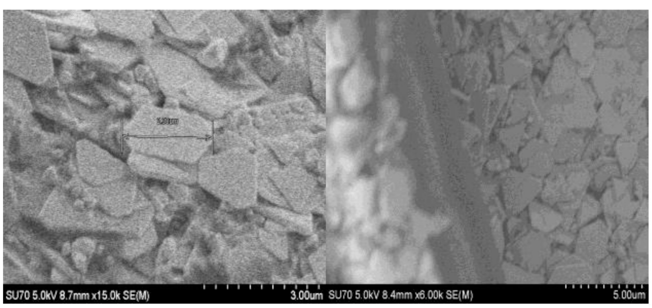


FIGURE 17. (Left) Silver (Ag) particles on fabric antenna (CKA) with interface layer. (Right) Silver (Ag) particles on fabric antenna (CKA) without interface layer.

this phenomenon, scanning electron microscopy (SEM) was used (see Figure 17).

In observing the SEM images, the silver (Ag) particles on the fabric antenna with the interface layer ink are adhered to the surface of the fabric substrate, i.e., they don't blead into the fabric threads unlike the fabric antenna without the interface layer where the silver particles blead through the fabric substrates between the threads, giving way to non-uniform conductive particle distribution.

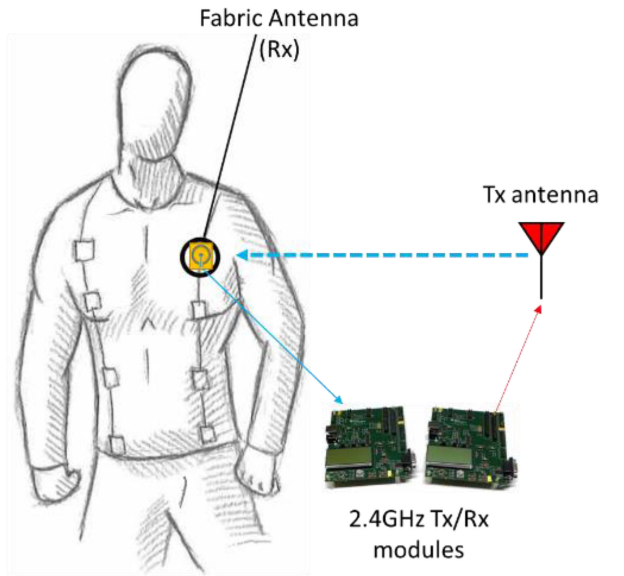


FIGURE 18. Link budget analysis experimental setup.

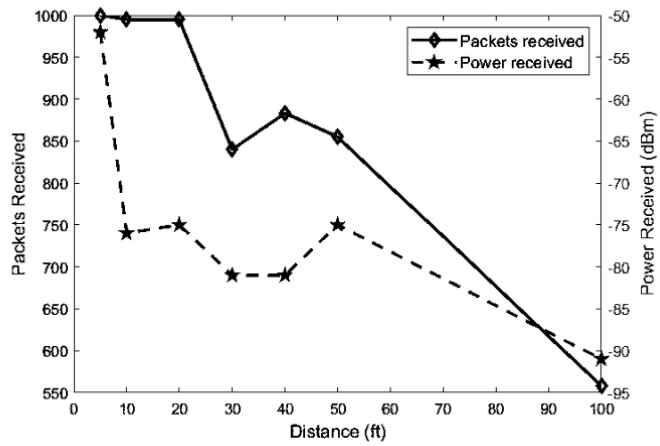


FIGURE 19. Power and data packets received with respect to increasing distance between transmitting and receiving antenna.

Next, the link budget analysis is performed experimentally by placing the wearable antenna on a mannequin that simulates the human torso. (see Figure 18).

A CC2530 development kit from Texas Instruments [10] was used. A standard monopole transmitting antenna with 0 dBm power was used on the transmitting module while the fabric antenna (CKA) with interface layer was connected to the receiving module. 1000 packets of known data was transmitted over varying distances between the transmitting and receiving antennas and power along with packets received was recorded (see Figure 19).

According to data obtained, the fabric antenna (CKA) with interface layer showed significant reception sensitivity with complete data packets received up to 20ft away

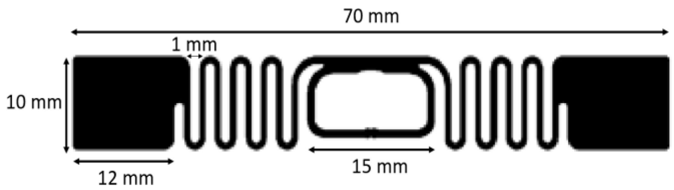


FIGURE 20. RFID tag design with dimensions.

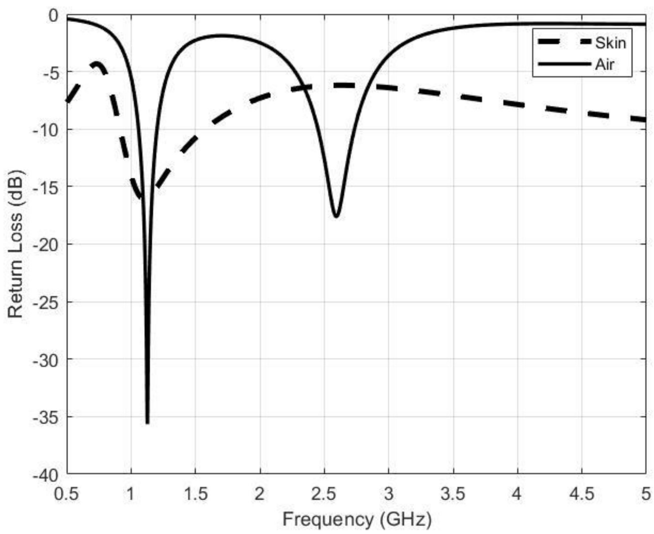


FIGURE 21. Return loss of simulated antenna in HFSS.

from the transmitting antenna along with power sensitivity of −50dBm. This provides commercial and practical viability when using these antennas for implantable device communication systems.

III. WEARABLE RADIO FREQUENCY IDENTIFICATION TAGS FOR COMMUNICATION WITH EXTERNAL READERS

In this section, developments in the fabrication of wearable RFID tags is presented. In recent years, the exploration of incorporating RFID into wearable devices has increased, and other approaches include embroidering conductive thread [11], sewing conductive fabric, and knitting conductive yarns. These types of RFIDs are predominately made to act as environmental sensors to detect moisture and temperature, for example [12]. An element that is missing from these applications is motion tracking, including body-relative motion and location monitoring [13], [14]. This section presents a method of fabricating wearable RFIDs which utilizes screen-printing [15] the antenna directly onto the fabric substrate for motion tracking capabilities. The antenna presented here operates at 915 MHz frequency (see Figure 20).

The antenna was simulated in ANSYS HFSS on a fabric substrate with skin underneath. This revealed a resonant frequency in the range of approximately 800 MHz to 1.6 GHz on skin. The resonant frequency of the antenna when simulated in air shares a narrow bandwidth within the aforementioned range.

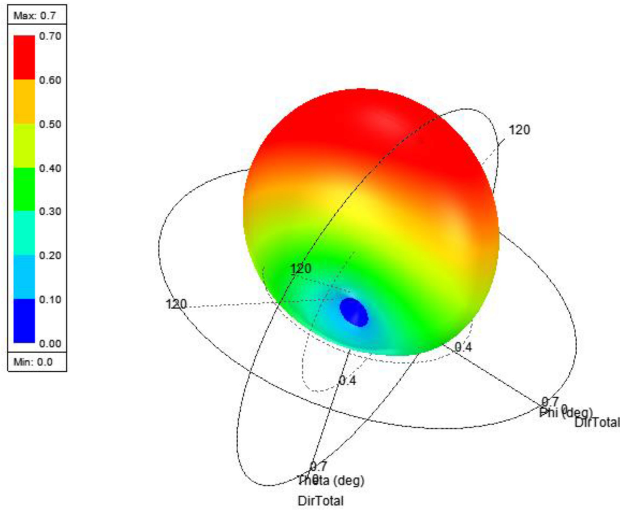


FIGURE 22. Directivity of RFID on skin at 915 MHz.

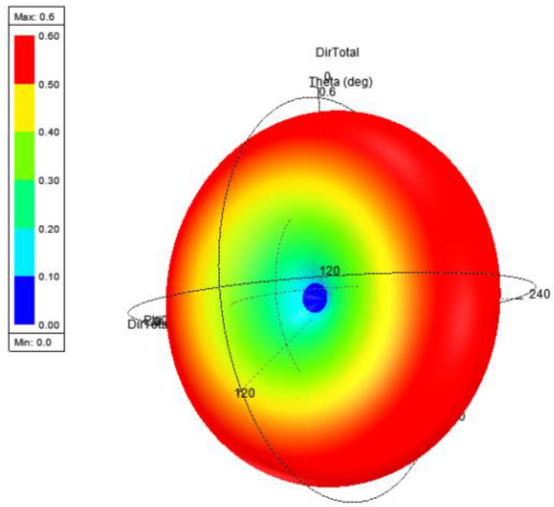


FIGURE 23. Directivity of RFID in air at 915 MHz.

FIGURE 24. Screen printed RFID on skin gel.

The RFID was simulated on a skin and air substrate and radiation pattern recorded (see Figures 22 and 23).

In order to fabricate the RFID tag in this study, conductive ink by NovaCentrix (FLX15) was used for

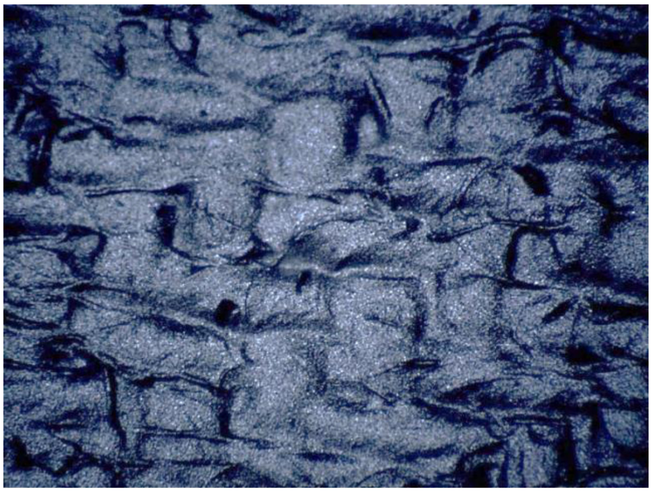


FIGURE 25. Microscope image of FLX15 conductive ink adherence on cotton/viscose fabric.

FIGURE 26. RFID reader setup in corridor.

antenna fabrication. Like the ink used for the previous antenna, this conductive ink consisted of silver particles [16]. Screen-printing with a 156 mesh screen was utilized to print the antennas on fabric (60% Cotton, 40% Viscose). Based on measurements of various fabric contents [17], this fabric composition has the highest flex after screen printing with the greatest conductivity for the given application. For the composition of this fabric with NovaCentrix FLX15, the measured sheet resistance is 6.5 $m\Omega/mm^2$ when screen printing (see Figure 25). The IC chip used is the NXP UCODE G2iL, secured with NovaCentrix conductive adhesive. Before testing, the fabric RFID was secured to a skin gel to simulate the fabric antenna being worn (see Figure 24).

A UHF RFID reader was set up at the end of a corridor to test the screen-printed antennas (see Figure 26). The reader stood at body-level while attached to a laptop for data reading. This setup was used to record the furthest distance between the reader and antenna at which transmission

FIGURE 27. Corridor test results.

would occur. The reading software output no data when the RFID could not be read at the given distance, but output the name of the tag to show when transmission occurred.

After testing three screen-printed RFIDs, their maximum distances were 1.4-2.6 meters from the reader (see Figure 27). This results in an average of 2.2 meters. It is hypothesized that the presence of the skin-mimicking gel behind the antenna decreases the transmission distance, as the difference in transmission distance with and without the skin gel is about 6 meters.

IV. CONCLUSION

In this paper, we focused on unified fabric antennas capable of communication with a subcutaneously implanted sensor in the ISM band (2.4 GHz, 5.8 GHz). A new antenna topology; Coplanar Keyhole, was designed and implemented for a unique-axis (z-axis) radiation pattern. This ensured maximum antenna gain going into the body when mounted, communicating with an implantable sensor. The fabric antennas were fabricated using screen printing technology with a 230 mesh on 18% Spandex 82% Nylon blend fabric. Conductive ink by NovaCentrix with silver particles was used for the conductive elements of the antenna. A 5.8GHz antenna (CKA) was fabricated on to the fabric substrates and return loss recorded. When screen printing, ink blead through the fabric was observed. This caused a direct shift in resonant frequencies and dual band behavior. This was rectified by introducing a non-conductive ink layer forming an interface between the conductive elements and fabric substrate of the antenna. The antennas were tested for data transfer and showed a viable range of 20ft before any data loss during transmission. The antennas were also tested for wash sustainability and then tested for their return loss. After 5 washes all antennas showed return losses < -10 dB at the designed frequencies. While showing promising results in terms of long-term usability effects of high dielectric interface layer require significant research. Also, newer antenna topologies for sensing medical applications need to be investigated.

A new wearable RFID tag antenna topology was presented which was designed to operate at 915 MHz (UHF). The fabric RFIDs were screen printed using a 156 mesh with NovaCentrix FLX15 conductive ink on 60% Cotton 40% viscose fabric. Conductive adhesive was used to secure the IC chip to the fabric. The RFIDs were secured to skin gel to simulate being worn on the body. This resulted in a maximum transmission distance of 2.6 meters. It is hypothesized that the skin gel dramatically decreases this distance, and future research will include accounting for this change. Future research must include integrating these RFIDs into clothing and optimizing them for durability and long-term use.

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