Fabrication and Reliability Evaluation of Passive UHF RFID T-shirts

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Abstract— **In this paper, we present textile antennas fabricated for T-shirt RFID applications by cutting from commercially available electro-textile, by sewing with conductive thread, and by 3D printing with stretchable silver ink on a 100 % cotton fabric. The ready tags with attached ICs are coated with a protective stretchable encapsulant. The wireless performance of the T-shirt tags is evaluated initially as well as after seven washing cycles, followed by nine washing-drying cycles in a household washing and drying machines. The initial read ranges of all kinds of tags, when measured on-body, are around 3.5 meters. Based on the reliability testing results, the coating effectively protects the components from cyclic washing and drying.**

Keywords— 3D Printing; electro-textiles; embroidery, passive UHF RFID; textiles; T-shirts; washing; wearable electronics

I. Introduction

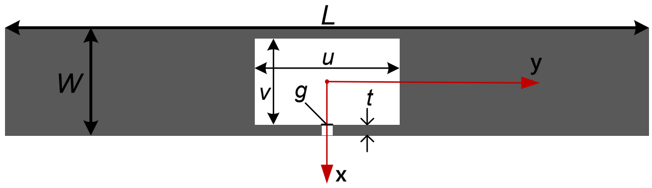
Wireless body area networks (WBAN) offer great potential for identification, monitoring, and communication in versatile application areas, e.g., in healthcare, welfare, and public safety [1][2]. One extremely potential wearable technology solution are passive ultra high frequency (UHF) radio-frequency identification (RFID) tags integrated into clothing [3][4], which will be the focus of this study. Wearable applications require the technology to be an integral part of clothing and to endure repeated mechanical stresses, moisture, and washing. This leads to the challenge of creating flexible and washable electronics structures, directly into clothing.

Antennas are critical enabling parts of all WBAN solutions. Conductive fabrics, i.e., electro-textiles, are a great example technology, which can be used to utilize cost-effective antennas for wearable solutions [5][6]. Electro-textile materials are easy to cut and can be unnoticeably embedded into traditional textiles. Further, sewing with conductive thread is a versatile manufacturing method, which has great possibilities in clothing-integrated antennas, due to its compatibility with various textile materials and easily modified conductive patterns [7]-[10]. In addition, 3D direct-write dispensing, a form of 3D printing, is an efficient additive manufacturing method, which enables the printing of complex antenna geometries with micron resolution accuracy. It is possible to 3D print versatile antenna materials on different types of fabric substrates [3]. These three techniques also provide the foundation for wearable identification and sensing applications by fabricating passive UHF RFID tags integrated into textiles.

In this paper, we present textile RFID tag antennas, fabricated by cutting from commercially available electro-textile, as well as by embroidering with conductive thread and by 3D printing with stretchable silver ink on cotton shirts. The ready tags equipped with ICs are coated with a protective encapsulant. All tags experience 7 washing cycles and 9 washing-drying cycles in a household washing and drying machines. The wireless performance of the tags integrated into shirts are evaluated, on body, before any reliability testing and after each testing cycle.

II. Fabrication of the Tags

Fig. 1 shows the geometry and dimension of the used wearable antenna. This dipole antenna design has been originally presented in [8] and has been optimized to work near the human body by using a human body model in ANSYS HFSS version 15. All the RFID tag antennas were fabricated on the upper back of a 100 % cotton T-shirt.



t	*g*	*L*	*W*	*u*	*v*
2 mm	2 mm	120 mm	20 mm	27 mm	16 mm

Fig. 1. The design and dimensions of the wearable UHF RFID tag antenna

The electro-textile antennas were utilized from nickel plated Less EMF Shieldit Super Fabric (Cat. #A1220), which has the hot-melt glue on the backside. The tag antennas were ironed directly on the cotton shirts. The electro-textile exhibits sheet resistance of approximately 0.16 Ω/□.

The embroidered antennas were utilized on the cotton fabric with Husqvarna Viking embroidery machine, using multifilament silver plated thread (Shieldex multifilament thread 110f34 dtex 2-ply HC). The resistance of the yarn is

500±100 Ω/m, and the diameter is approximately 0.16 mm. Based on the excellent results in [8], where only the antenna contour was sewed, we chose to only embroider the outline of the antenna. This method saves significant amounts of conductive thread and fabrication time, but does not significantly affect the antenna performance.

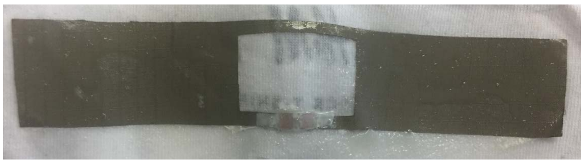
The 3D printing was completed directly on the cotton substrate by nScrypt tabletop series 3D direct-write dispensing system with a stretchable silver conductor (DuPont PE872). By adjusting the printing parameters, the printing system can produce a controllable ink flow, precise starts and stops, and the ability to utilize a wide range of material viscosities. The main printing parameters are defined in Table 1. Finally, the 3D-printed antennas were cured in 110 ºC for 15 minutes.

Table 1**.** 3D printing parameters

Parameter	
Material feed pressure	16.9 Psi
Printing spacing	125 microns
Printing angle	0°
Inner diameter of tip	125 microns

The RFID IC (integrated circuit) utilized in this study was NXP UCODE G2iL RFID IC, provided in a strap, which has copper pads on a plastic film. We attached the 3 × 3 mm^2 copper pads to the antennas using conductive epoxy (Circuit Works CW2400). The used IC has a wake-up power of −18 dBm (15.8 μW).

(a)



(b)

(c)

Fig. 2. The fabricated tags integrated into T-shirts: (a) 3D printed tag antenna, (b) Electro-textile tag antenna, (c) Embroidered tag antenna.

Finally, to protect the fabricated RFID tags from the harsh environment in washing and drying machines, both sides of the tags were coated with a stretchable protective encapsulant (DuPont PE772). The coating was brush-painted to fully cover the tags and the coated tags were dried in 100 ºC for 60 minutes. Fig. 2 shows the ready-made passive UHF RFID T-shirt tags.

III. Wireless Measurements

The wireless performance of the tags was evaluated using Voyantic Tagformance RFID measurement system. It contains an RFID reader with an adjustable transmission frequency (800-1000 MHz) and output power (up to 30 dBm) and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test.

During the test, we recorded the lowest continuous-wave transmission power (threshold power: P_{th}) of the T-shirt tags. Here we defined P_{th} as the lowest power at which a valid 16-bit random number from the tag was received as a response to the query command in ISO 18000-6C communication standard. In addition, the wireless channel from the reader antenna to the location of the T-shirt tag under test was first characterized using a system reference tag with known properties. This enabled us to estimate the attainable read range of the tag (d_{tag}) versus frequency from

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}} \quad (1)$$

where λ is the wavelength transmitted from the reader antenna, Pth is the measured threshold power of the measured T-shirt tag, Λ is a known constant describing the sensitivity of the system reference tag, $Pth*$ is the measured threshold power of the system reference tag, and EIRP is the emission limit of an RFID reader given as equivalent isotropic radiated power. We present all the results corresponding to EIRP = 3.28 W, which is the emission limit for instance in European countries.

All the T-shirt tag measurement were completed both in an anechoic room and in an office environment. Both measurement environments are shown in Fig. 3. During the wireless measurements, the female test subject wore the T-shirt and stood in a distance of 1 meter from the RFID reader antenna.

(a) (b)

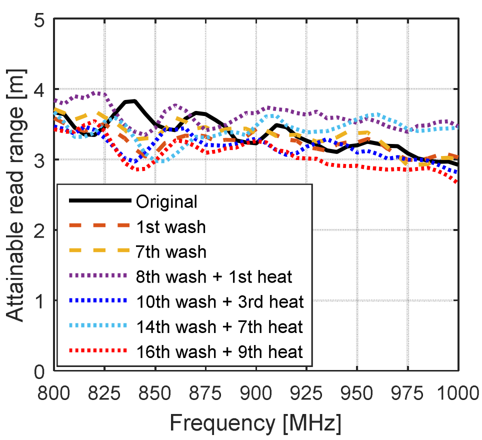
Fig. 3. Wireless measurements done in (a) Anechoic room, (b) Office conditions.

IV. Results and Discussion

Firstly, the original on-body performance of the T-shirt-integrated RFID tags was evaluated in an anechoic room and in an office. The initial read ranges of all kinds of tags, when measured on-body, were around 3.5 meters**.** Next, the T-shirts were worn during the day and washed in a household washing machine in the evening. The washing was done in 40 °C without detergent and one washing cycle lasted for 22 minutes. The T-shirts were dried in room conditions. The tags were measured after each washing cycle and the results are shown in Figs. 4-6. After the eighth washing test, a normal household drying machine was started to use to dry the washed T-shirts. The drying cycle lasted for 1 hour and 30 minutes. Altogether 9 washing + drying cycles were done, after the original 7 washing cycles. The tags were measured on-body after each washing + drying cycle, in an anechoic room and in an office, and also these results are shown in Figs. 4-6.

As can be seen from Fig. 4, the washing and drying cycles did not have major effects on the electro-textile tags. The read ranges of the electro-textile tags decreased less than 0.5 meters after 7 washing cycles and 9 washing + drying cycles. However, as can be seen, human body causes significant variations to the measurement results. In case of the embroidered and 3D-printed tag antennas, the read ranges of the tags decreased around 0.5-1 meters, after all the washing and drying cycles. It should be noted that all types of tags maintained read ranges of more than 2 meters, after daily wearing and these harsh washing and drying tests.

These washing reliability results are very promising, when compared to earlier results. In [6], washing had a significant impact on non-coated, glue-coated, and textile moisture protection spray-coated electro-textile tags. The read ranges of the tags decreased 3.5 meters, 2 meters, and 3 meters respectively, from their initial values, after 10 washing cycles in a washing machine. Moreover, in [11], the read ranges of non-coated embroidered tags decreased from 6 meters to 3 meters after 16 washing cycles. The comparisons indicate that the protective coating utilized in this work could protect textile-integrated RFID tags during normal use.



(a)

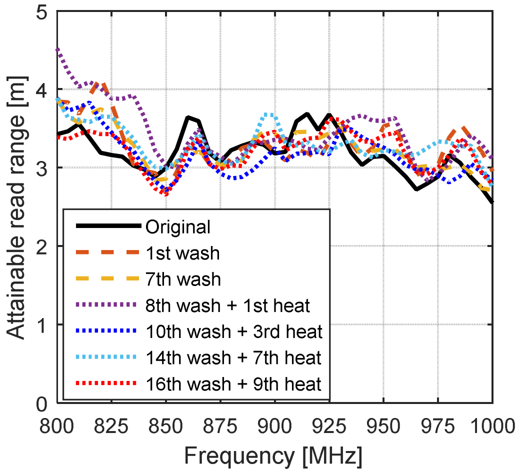


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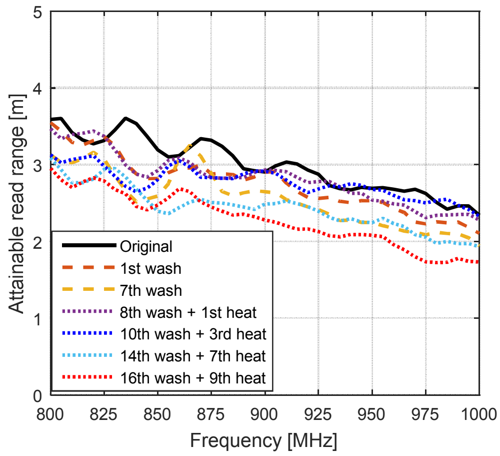
Fig. 4. Wireless performance of electro-textile tags after washing and drying testing in: (a) Anechoic room, (b) Office environment.



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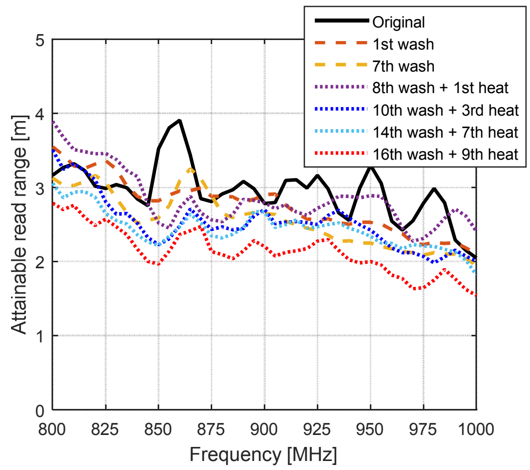
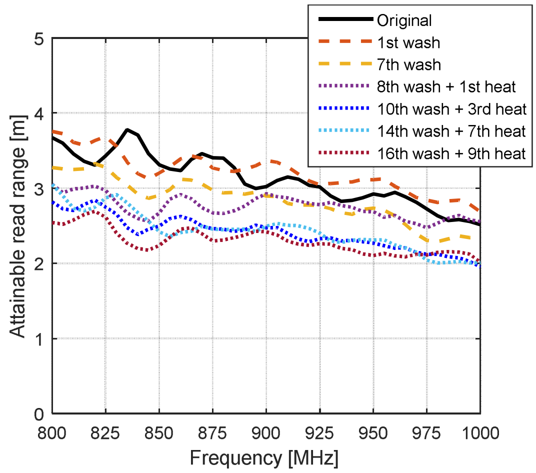
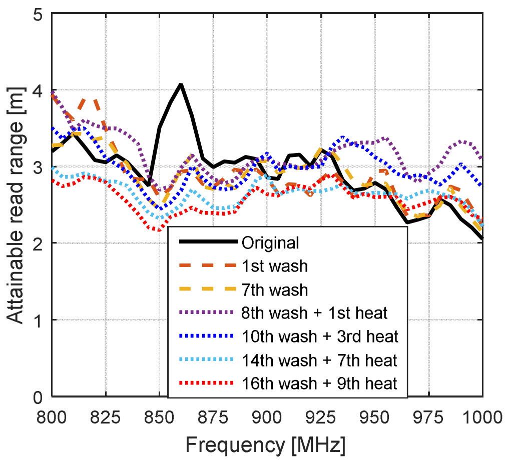


(b)

Fig. 5. Wireless performance of embroidered tags after washing and drying testing in: (a) Anechoic room, (b) Office environment



(a)



(b)

Fig. 6. Wireless performance of 3D-printed tags after washing and drying testing in: (a) Anechoic room, (b) Office environment

V. CONCLUSIONS

We fabricated and wirelessly evaluated three types of passive UHF RFID tags integrated into T-shirts. The tags with electro-textile, embroidered, and 3D-printed antennas were coated with a protective encapsulant and tested for daily on-body wearing, machine washing, and machine drying. The T-shirt tags were measured on human body both in an anechoic room and normal office environment. The initial read ranges of all kinds of tags, when measured on body, were around 3.5 meters. The tags showed similar performance in both measurements environments, which supports their practical use in different types of environments. After the washing and drying cycles, all tags still achieved read ranges of more than 2 meters, throughout the global UHF RFID frequency band. These results are very promising when considering practical integration of passive RFID technology into clothing. The next step is to carry out more washing and drying cycles and do tests with detergent. Further, we will test integration of these tags into different types of clothing, such as shirts made from thicker fabrics and stretchable sports clothing.

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