Reliability Evaluation of Wearable RFID Tags: Design and Fabrication of a Two-Part Textile Antenna

Abstract

Passive RFID (radio frequency identification) -based technology is a convincing approach to achieve versatile energy- and cost-efficient wireless platforms for future wearable applications. By using two-part antenna structures, the antenna-electronics interconnections can stay non-stressed, which can significantly improve the reliability of the textile-embedded wireless components. In this paper, we fabricate two-part stretchable and non-stretchable passive UHF (ultra-high frequency) RFID textile tags using electro-textile and embroidered antennas, and test their reliability immersed as well as under cyclic strain. The results are compared to tags with traditional one-part dipole antennas fabricated from electro-textiles and by embroidery. Based on the achieved results, the initial read ranges of the two-part antenna tags, around 5 meters, were only slightly shorter than the one-part antenna tags. In addition, the tags with two-part antennas can maintain high performance in a moist environment and during continuous stretching, unlike the one-part antenna tags, where the antenna-IC attachment is under a stress.

Key words: RFID, E-textile antenna, Embroidery antenna

1. Introduction

Passive RFID (radio frequency identification) -based technology has been recognized as a compelling approach to utilize energy- and cost-efficient wireless platforms for future body-centric applications. With the help of wearable passive UHF (ultra high frequency) RFID equipment, the identification, access control, as well as remote monitoring of movement and physiological parameters of a person can be achieved unobtrusively. As the technology is passive, no onboard power sources or complex systems are needed. A passive tag is only composed of an antenna and an IC (integrated circuit), and it uses the power emitted from the reader to energize itself and backscatter its data. The wearable RFID technology could be utilized in healthcare applications in hospitals as well as in home environments. Further application areas include wearables for wellbeing and sports [1]-[4]. For further information on UHF RFID technology, a comprehensive introduction is provided in [5].

Due to these great possibilities of textile-integrated passive wireless platforms, design and fabrication of wearable antennas and interconnections has been an active research area during the recent years. Textile-integrated antennas, for example electro-textile antennas [6][7] and embroidered antennas [8][9], enable the seamless integration of wireless components into wearable identification and sensing applications. Electro-textile antennas are cost-effective, lightweight, and easy to integrate with clothes [6][7][10][11]. Embroidery with conductive yarn is a simple manufacturing method with great possibilities due to its compatibility with various textile materials [12][13][8][9]. In embroidery, we have a full control of the conductive pattern: shape, stitch density, and stitch type [14][9]. In addition to conductor and antenna fabrication, sewing has also been found to be a highly useful method for embedding electrical interconnections into textile materials [13][15]-[17].

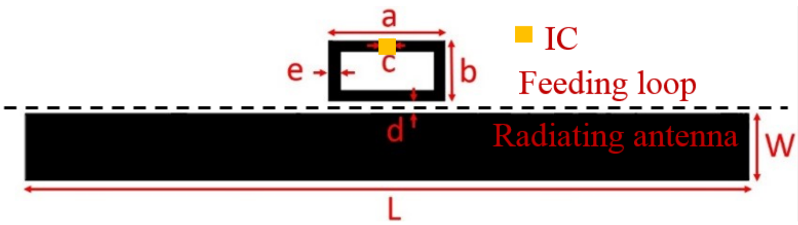
There are still some challenges of wearable RFID tags that need to be resolved before wider field use. In wearable applications, where stretching and bending is common, the antenna-electronics interconnections are usually under a strong stress, which may cause electrical and mechanical reliability challenges for the interconnections [18]. Further, since the antenna's structure changes when stretched, it may cause the antenna-IC matching to change [7][9][18]. Another major challenge lies in the effects of moisture, which is commonly involved in wearable applications [19]-[21]. Washing hands or face, staying outdoors when it is raining or simply sweating may cause clothing-integrated electronics to get wet. In case of RFID components, the response from the passive tag is affected by the prevailing circumstances and surrounding materials, such as moisture and dry/wet textile. The increased moisture can alter the electromagnetic properties of textile materials, which contain many air cavities [22]. The changed permittivity of the textile material can thus create a mismatch between the tag antenna and the IC. The increased moisture can also increase the losses in the textile substrate, degrading the overall tag performance [23]-[25].

As previously presented in [26], the antenna-IC connection can be implemented by inductive coupling between two designed windings, connected to the IC and to the patch antenna ground. Thus, the galvanic connection between the IC and antenna can be avoided [26]. In this paper, we optimized a two-part antenna structure in order to solve the reliability problems of wearable RFID tags caused by human's activities----moisture and mechanical stresses. The separate antenna structures contain a radiating antenna and a feeding loop with the IC. These two parts of the antenna are connected by inductive coupling and thus the IC part can be placed to a small distance from the radiating antenna. Then, the small feeding loop part of the antenna, including the antenna-IC interconnection, can be protected from mechanical stresses and moisture, which can significantly improve the reliability of the RFID tag component. We fabricate two-part stretchable and non-stretchable passive UHF RFID textile tags using electro-textile and embroidered antennas, and test their reliability in immersing conditions as well as under cyclic strain. In addition, traditional one-part dipole antennas were fabricated from the same materials as the two-part tags, in order to compare their performance in different conditions.

2. Tag fabrication

A. Two-part antennas

The structure and size of the two-part antennas is shown in Fig 1. The antenna design has two separate parts, the feeding loop and the radiating antenna, with a 2.5 mm gap between them. Thus, it is possible to attach the IC to a non-stretchable substrate, while the radiating antenna can be fully stretchable. We fabricated two-part electro-textile tags and two-part embroidered tags.



a	b	c	d	e	W	L
21.6 mm	11.3 mm	2 mm	2.5 mm	1.9 mm	12.6 mm	165.7 mm

Fig. 1. The structure of the two-part antenna.

To fabricate the electro-textile two-part antennas, we cut the radiating antenna from Less EMF Stretch Conductive Fabric, which is a commercial stretchable silver textile material, fabricated by plain knitting [27]. The feeding loop was cut from non-stretchable commercial copper woven textile, Less EMF Pure Copper Polyester Taffeta Fabric [28]. The used electro-textile materials are shown in Fig. 2. The electro-textile antennas were cut using a laser cuter (Epilog Fusion Laser Model 13000).

For the embroidered two-part tag, the radiating antenna contour was embroidered on a plain knitting elastic band, using Husqvarna Viking sewing machine and conductive multifilament silver plated yarn (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. The embroidery process is shown in Fig. 3. The DC linear resistivity of the yarn is 500±100 Ω/m and the diameter is approximately 0.16 mm. The feeding loop, on the other hand, was embroidered on a non-stretchable 100 % cotton woven fabric. The substrate materials are shown in Fig. 2.

The final substrate used for the two-part tags was 2 mm thick EPDM (Ethylene-Propylene-Diene-Monomer) with a dielectric constant and loss tangent of 1.26 and 0.007, respectively, at 915 MHz. The dielectric constant and loss tangent were measured by Agilent 85070E dielectric probe kit [29]. These two parts of the antenna design were integrated on this cell rubber foam substrate as shown in Fig. 4. The feeding loop was glued with a textile glue and the radiation antenna body was attached with double sided tape, which can be removed and attached several times.

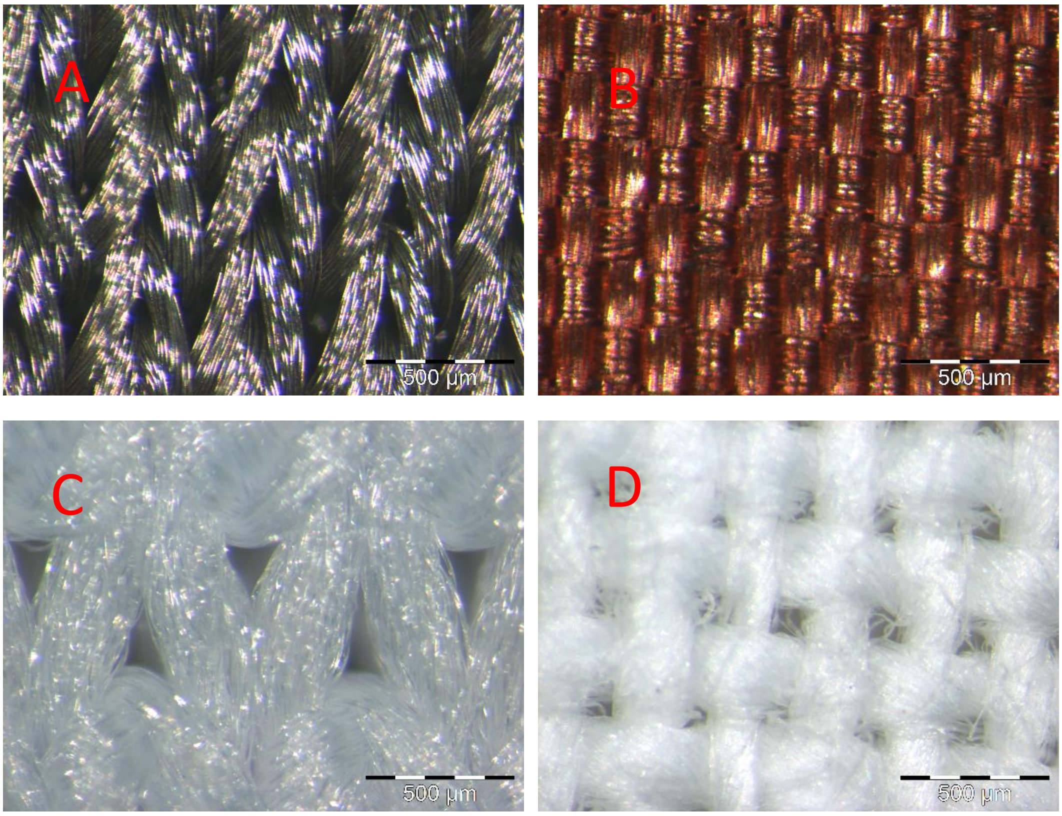


Fig. 2. Microscope pictures of the used fabrics: A. Stretchable silver knitted fabric, B. Non-stretchable copper woven fabric, C. Knitted elastic band fabric, D. 100 % cotton woven fabric.

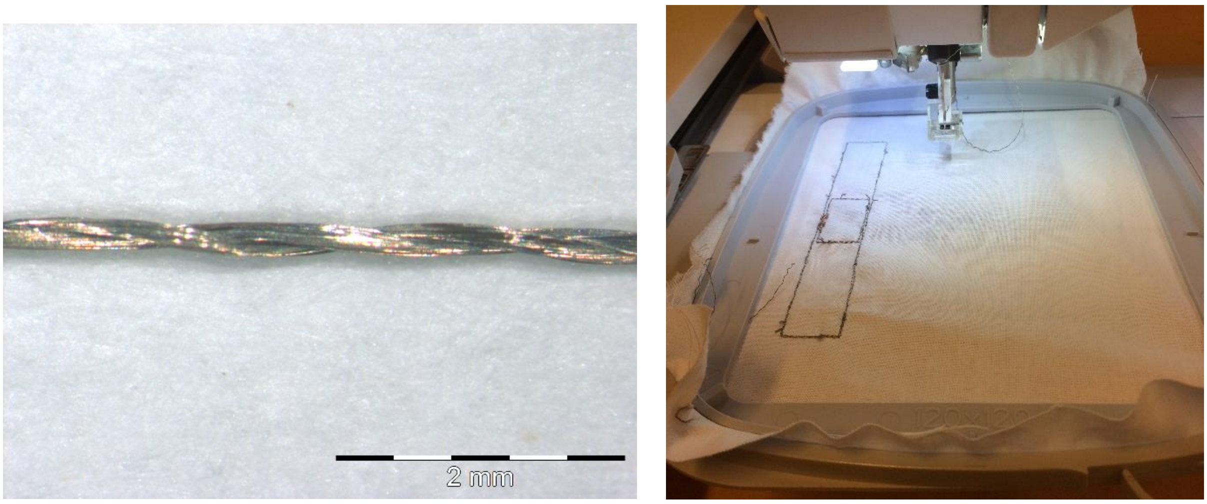


Fig. 3. A microscope picture of the used conductive yarn (left) and the embroidery machine (right).

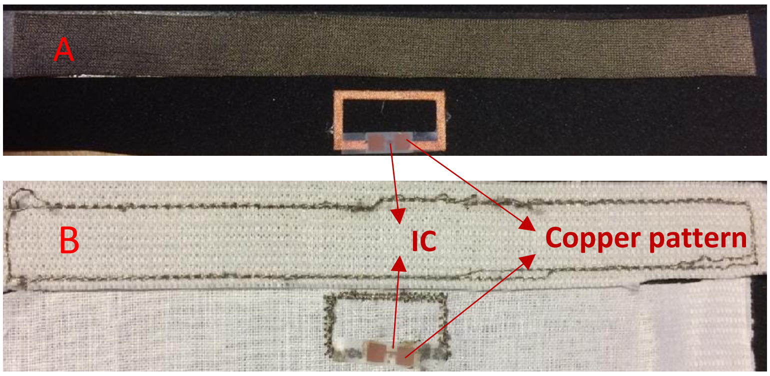
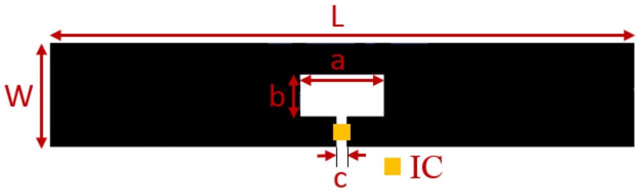


Fig. 4. Electro-textile two-part tag (A) and embroidered two-part tag (B).

B. One-part antennas

The structure and parameters of the one-part antenna are shown in Fig 5. It is a dipole antenna with a matching slot in the middle of the antenna body. We fabricated one-part electro-textile tag antennas from the stretchable silver fabric and from the non-stretchable copper fabric. Further, we fabricated embroidered one-part tag antennas on cotton and on elastic band. These tag antennas are shown in Fig. 6.



a	b	c	W	L
14.3 mm	8.125 mm	2 mm	20 mm	100 mm

Fig. 5. The structure of the one-part antenna.

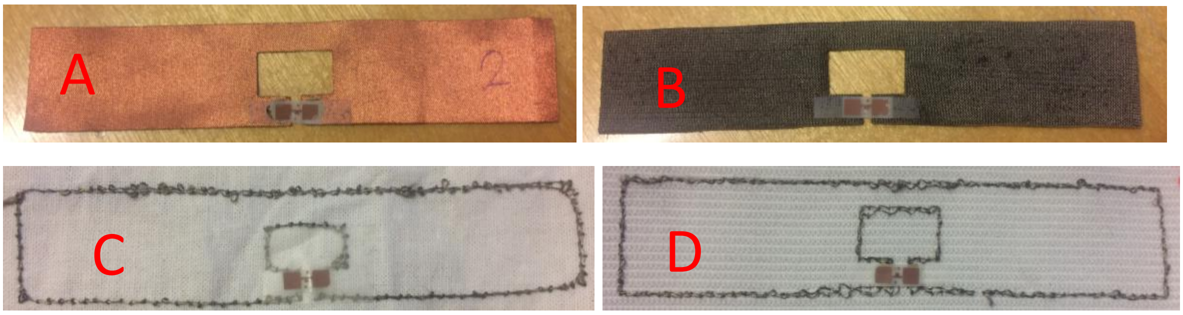


Fig. 6. One-part antenna tags: A. Non-stretchable copper woven fabric tag, B. Stretchable silver knitted fabric tag, C. Embroidered tag on 100 % cotton woven fabric, D. Embroidered tag on knitted elastic band fabric.

C. IC attachment

After antenna fabrication, in order to establish fully functional RFID tags, NXP UCODE G2iL series RFID ICs, provided by the manufacturer in a strap with copper pads, as shown in Fig. 7, were attached to the antennas with conductive silver epoxy (Circuit Works CW2400). For each tag type, four samples were fabricated to also evaluate the reproducibility. Ready-made two-part and one-part tags are shown in Fig 4 and Fig. 6, respectively.

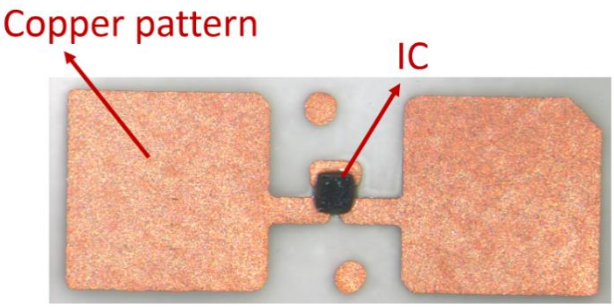
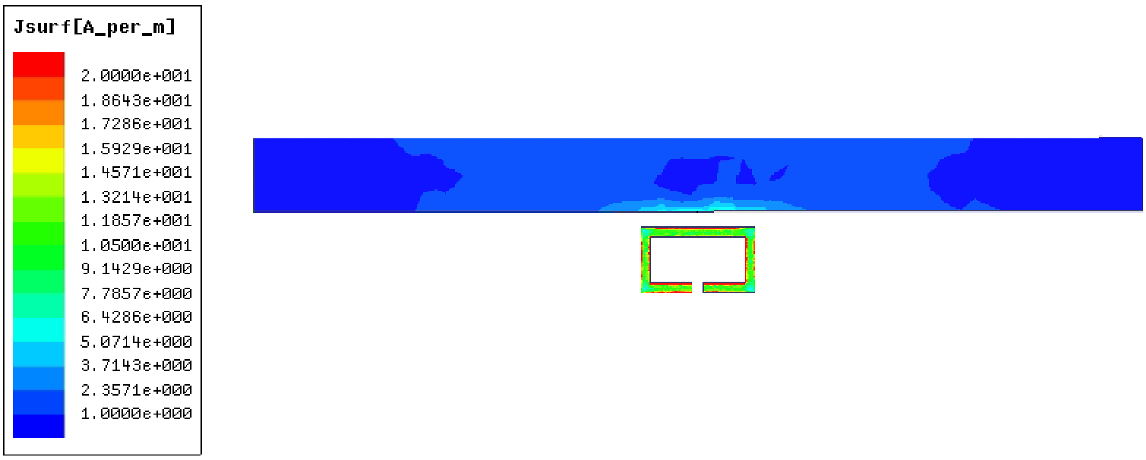


Fig. 7. The used NXP UCODE G2iL series RFID IC.

3. Simulations and wireless measurements

The optimization of the antenna structure was based on electromagnetic modelling in ANSYS High Frequency Structure Simulator (HFSS). In the simulation of the two-part antenna, 0.94 W was delivered to the antenna. As can be seen from Fig. 8, the current density at 915 MHz was high around the feeding loop and the nearby antenna edges. For the one-part antenna, 0.57 W was delivered to the antenna, and also here the current density was high around the matching slot, as shown in Fig. 8.

In simulation, we were searching for the optimized antenna dimensions. By adjusting the size of the feeding loop and the antenna body, we wanted to achieve the longest possible read ranges for the tags. Also, the current density in different parts of the tag antennas can be indicated by the simulation. According to current density, we can decide the needed density of conductive yarn at different antenna parts: significant amounts of time and conductive yarn can be saved in the embroidery of RFID tag antennas by only partially sewing them [30]. Especially dipole tags where only the border lines of the antennas have been sewed, meaning sewing fully only the parts where the current density is the highest, have showed excellent wireless performance [30]. This was also the starting point in our work.



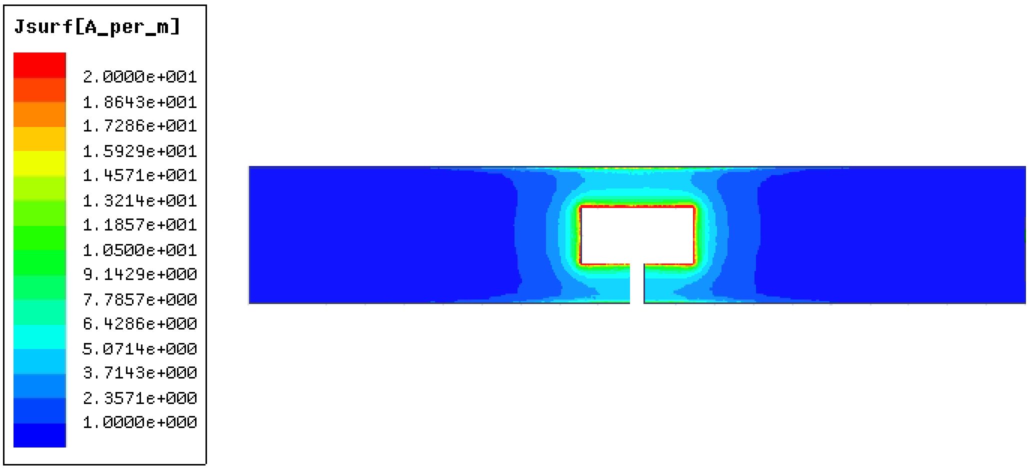


Fig. 8. The simulated current distributions at 915 MHz for the two-part antenna (top) and one-part antenna (bottom).

In this work, the ready-made tags were wirelessly measured in an anechoic chamber with Voyantic Tagformance RFID measurement system, as shown in Fig. 9. It contains an RFID reader with an adjustable transmission frequency (0.8…1 GHz) 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. The tested tags were placed in an anechoic chamber to prevent any multi path effect.

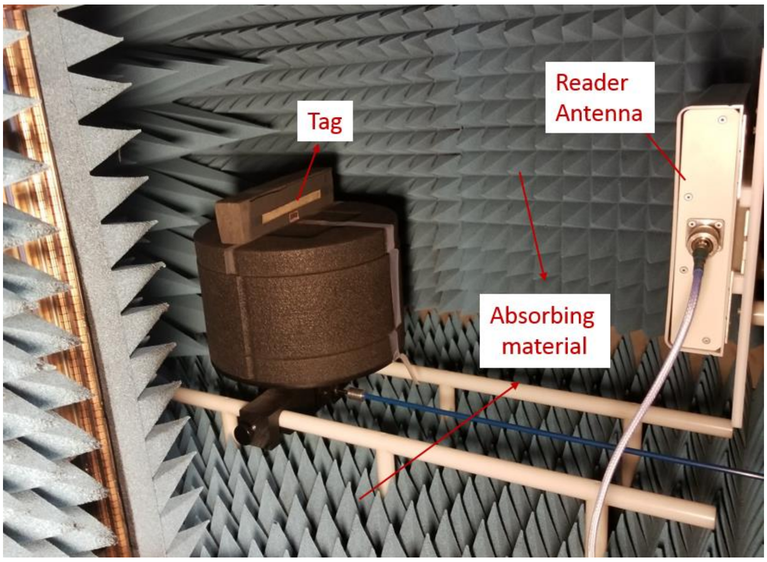


Fig. 9. Tags measured in an anechoic chamber.

Firstly, the wireless channel from the measurement system reader antenna to the location of the evaluated tag under test was characterized using a system reference tag with known properties. During actual testing, we recorded the lowest continuous-wave transmission power (threshold power: P_{th}) of each tag, i.e., 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. As has been detailed in [18], this enabled us to estimate the attainable read range of the measured tag (d_{tag}) versus frequency from

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th^*}}{P_{th}}}, \tag{1}$$

where λ is the wavelength transmitted from the reader antenna, Pth is the measured threshold power of the 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 Effective Isotropic Radiated Power (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 in European countries.

4. Reliability testing and measurement results

The initial read ranges of different types of tags were measured to evaluate their wireless performance. The read range results of all fabricated tags are shown in Fig. 10. As can be seen, the one-part non-stretchable copper textile tag had the highest read range, which was around 11 meters. The embroidered one-part tag, both on an elastic band and on cotton, had a peak read range of 6.5 meters. Further, the one-part stretchable silver textile tags achieved read range of 5 to 5.5 meters. The electro-textile and embroidered two-part tags also showed read ranges of around 5 meters. Thus, the initial read ranges of the two-part antenna structure tags seem to be only slightly shorter than the one-part antenna structure tags. Further, all fabricated tags showed read ranges of a few meters throughout the global UHF RFID frequency band (860-960 MHz). Here we present only one measurement result for each tag type, as all same type of tags showed similar performance, except the one-part stretchable silver textile tags, which all worked with a variation of 0.5 meters.

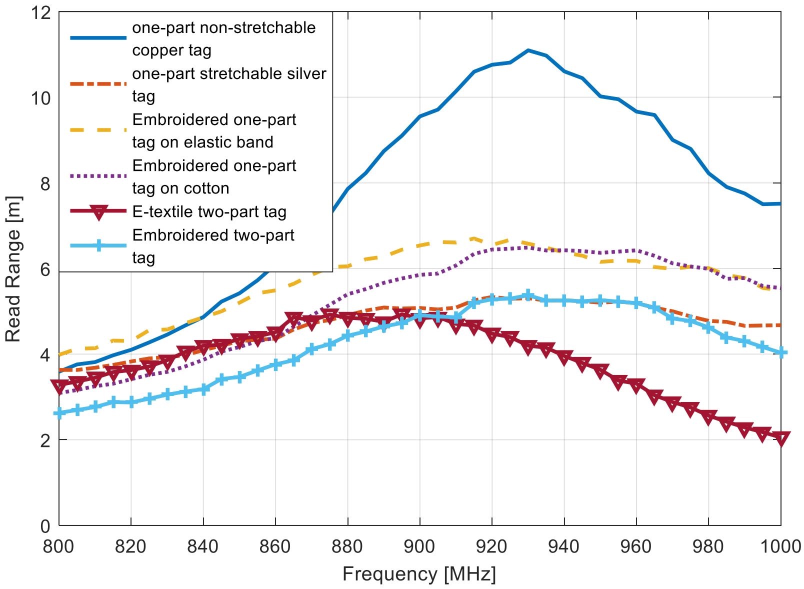


Fig. 10. The initial read ranges of all fabricated tags.

A. *Immersing test*

The purpose of the immersing test was to evaluate if these textile tags could be used near the human body, where sweating and moist environment may cause them to get wet. We tested the tags into room temperature tap water, to simulate real daily life conditions. In the immersing test, the tags were dipped into tap water for 2 seconds and measured immediately after that. They were then dried for 24 hours on an office table and measured again. In the case of the one-part antenna tags, the whole tag was placed into water. In case of the two-part antenna tags, only the radiating antenna (antenna without IC) was dipped into water. Again, we only present one measurement result for each tag type as the results of the same type of tags were similar.

As shown in Fig. 11 (A), for the one-part copper textile tags, after 2 seconds in water, the read ranges in the UHF RFID frequency band (860-960 MHz) decreased from 11 meters to 3-4 meters. Despite this significant change, the tag remains functional, and the read range returns to the original value, when the tag has dried for 24 hours. The copper textile is not a water absorbing material; instead, the water drops stay on the surface of the textile, where they also easily transfer near the IC part. The moisture on the antenna surface creates a mismatch between the tag antenna and the IC, and thus shifts the peak read range from around 940 MHz to somewhere outside the showed UHF RFID frequency band. In addition, drops of water on the antenna surface seem to be strongly degrading the overall tag performance.

The one-part stretchable silver textile tags achieved an initial read range of around 5 meters. As shown in Fig. 11 (B), the absorbed moisture actually increases the read range of the tag to 6 meters. This is most probably caused by the increased conductivity of the textile antenna, caused by the water absorbed into the antenna structure: The DC resistance of the antenna, measured from antenna corner to corner, decreased from 32 Ω to 20 Ω, when the antenna got wet. This is a phenomenon that needs to be studied further. After 24 hours, the read ranges returned close to the initial value. Most probably there is still some moisture present in the antenna structure, which then slightly affects the tag read range.

For the embroidered tags on cotton, the absorbed moisture caused a significant read range decrease, as can be seen from Fig. 11 (C). The cotton fabric absorbs moisture very well, which then strongly affects the tag performance. During the 24 hours of drying, the cotton substrate had completely dried, and the tag performance had returned to the initial. The change in the read range was not as significant for the embroidered tag on the elastic band, which does not absorb moisture as well as the cotton material. Further, the moisture seems to stay longer in the elastic band material, which shows in the tag performance also after 24 hours of drying, as shown in Fig. 11 (D).

As shown in Fig. 12, the read ranges of the electro-textile and embroidered two-part tags were initially around 5 meters. As shown earlier in Fig. 10 (B), the absorbed moisture increases the conductivity of the stretchable silver textile material, which also here caused the read range of the two-part electro-textile tag to increase around 0.5 meters, when it was wet. The read range of the wet embroidered two-part tag, on the other hand, decreased slightly, to 4 meters. In case of the embroidered tag, the radiating antenna was embroidered on the knitted elastic band fabric, which is a water absorbing substrate. When this part was dipped into water, the fabric substrate absorbed water, which decreased its sheet resistance to 0.5 MΩ/sq. Thus, the fabric substrate became slightly conductive, which also affected the shape of the radiating antenna embroidered on it. From simulations we can see that increasing the length of the radiating antenna decreases the read range of the tag. The read ranges of both two-part tags returned to the initial values after drying for 24 hours.

Based on these results, the two-part antenna structure can be considered more robust towards moisture than the one-part structure. As shown in Fig. 8, the current density is high around the IC area, which means that any moisture near the IC area can affect the tag performance. In addition, the antenna material has a significant effect on how the tag performance changes when the tag gets wet. The results are summarized in Table 1.

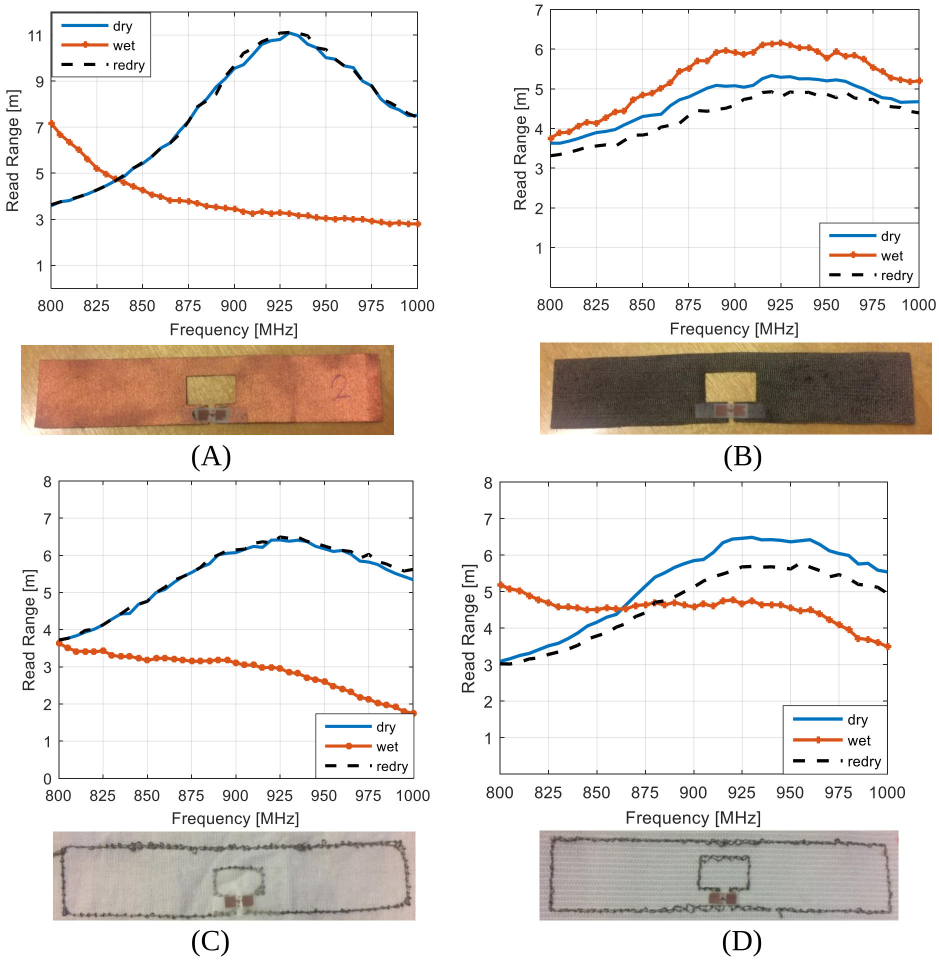


Fig. 11. Moisture test results of one-part tags: A. Non-stretchable copper textile tag, B. Stretchable silver textile tag, C. Embroidered tag on cotton, D. Embroidered tag on elastic band.

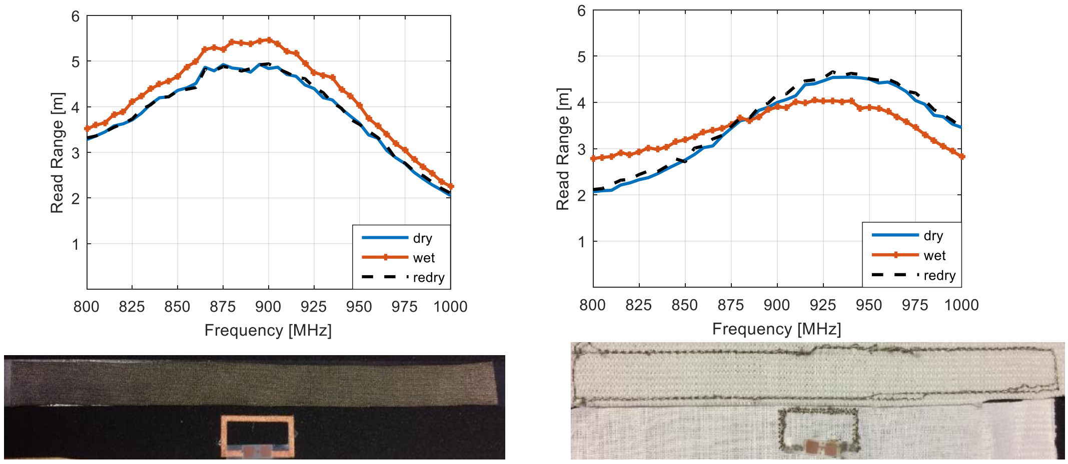


Fig. 12. Moisture test results of electro-textile (left) and embroidered (right) two-part tags.

B. Continuous stretching test

In the stretching test, all four kinds of stretchable tags were tested: the embroidered one-part tag on the elastic band, the one-part stretchable silver textile tag, and the electro-textile and embroidered two-part tags. The one-part tags we strained from their initial length of 100 mm to 110 mm and the two-part tags were strained from 165.7 mm to 167.7 mm. The tags' wireless performance, i.e., read range, was measured initially and after 1, 2, 5, 10, 20, 50, and 100 stretching cycles. Each stretching cycle lasted about 2 seconds. Finally, the tags were measured again 30 minutes after the stretching test.

The one-part embroidered tags were broken immediately when strained. The broken antenna-IC interconnection is shown in Fig. 14. However, All the one-part stretchable silver tags could be stretched a 100 times. The measurement results are shown in Fig. 14. As can be seen, the read range of the tag increased after each stretching cycle from the initial 5.5 meters to around 6.5 meter (after a 100 cycles). Thus, the stretching of the antenna effected the read range significantly. After 30 minutes of rest, the read range had already returned to 6 meters. Similar performance has been found in an earlier study with the same type of electro-textile tags [31]. It was reported that the increment in the antenna length produces a slight positive impact on the read range. Further, stretching may also temporarily influence the electromagnetic properties of the textile material, and thereby the impedance and radiation efficiency of the antenna.

Fig. 13. A broken antenna-IC interconnection in an embroidered one-part tag.

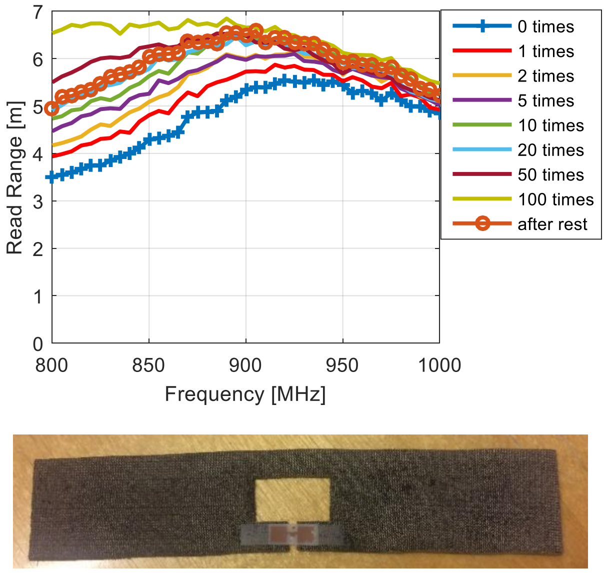


Fig. 14. Strain test results of a one-part electro-textile tag fabricated from stretchable silver fabric.

For the embroidered two-part tags, the attainable read range before any strain was measured to be around 5 meters, as shown in Fig. 15. After a 100 times of stretching, the read ranges were still 5 meters. Thus, the stretching did not have any effect on the tag performance.

For the tags with electro-textile antennas, the initial read ranges were measured to be around 5 meters at 890 MHz, and the read ranges after the first stretching cycle had a 20 MHz frequency shift to a lower frequency. Thus, the peak read ranges of the electro-textile tags moved from 890 MHz to 870 MHz after the first stretching cycle. However, the wireless performance of these tags was then settled and further stretching did not have any effect on the tag's performance. After 30 minutes, the peak read ranges of the electro-textile tags were still at 870 MHz, which means that the first stretching cycle had an enduring minor effect on the tag performance. This fabric has a little shape change when strained, and it does not return to its original shape immediately. The antenna is little longer and thinner already after the first strain, which affects the antenna-IC impedance matching. Based on the equation:

$$\lambda = \frac{c}{f};$$

Where λ is the wavelength, c is the speed of the light, f is the frequency. The wavelength is inverse proportion to the wavelength. When the length of the antenna increased, the matching point might shift to a lower frequency. Although this effect is not major, it should be taken into account when using this electro-textile material.

Based on these results, the two-part antenna design is a suitable antenna structure for stretchable tags, as the antenna-IC interconnections stays unharmed even during harsh strain. The results of the reliability test are summarized in Table 1.

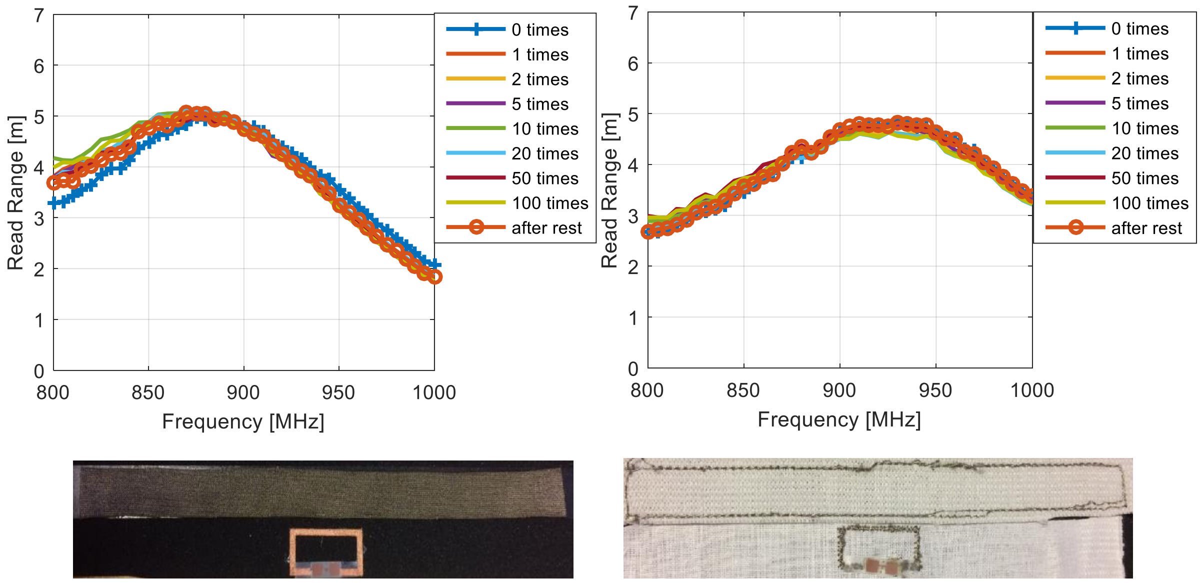


Fig. 15. Stretching test results of electro-textile (left) and embroidered (right) two-part tags.

Table 1. Reliability testing results.

	Immersing test			Stretching test			
	Initial	Wet	24 h	1 cycle	50 cycles	100 cycles	30 min
Electro-textile two-part tag	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$
Embroidered two-part tag	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$
One-part non-stretchable copper tag	$\geq 4m$	$< 4m$	$\geq 4m$	X	X	X	X
One-part stretchable silver tag	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$	$\geq 4m$
Embroidered one-part stretchable tag	$\geq 4m$	$\geq 4m$	$\geq 4m$	Break	Break	Break	Break
Embroidered one-part non-stretchable tag	$\geq 4m$	$< 4m$	$\geq 4m$	X	X	X	X

Break = Broke during testing, X = Non-stretchable fabric

Conclusions

In this paper, we presented one-part and two-part passive UHF RFID tags based on embroidered and electro-textile tag antennas. These two types of RFID tags were tested for immersing and continuous stretching, two common challenges of wearable wireless components. Initially, the one-part tags achieved peak read ranges from 5 meters to 11 meters, which were longer than the read ranges of the two-part tags, which achieved peak read ranges of around 5 meters. However, according to the results achieved in this study, unlike the one-part tags, where the antenna-IC attachment is under a stress, the two-part antenna designs can maintain high performance in a moist environment and during continuous stretching. They could be used in wearable applications, where textile-integrated RFID platforms need to be placed at a continually strained or immersing condition, e.g., for the purpose of moisture or movement monitoring. Both fabrication methods, embroidery with conductive yarn and cutting from conductive textile materials, were found to be useful for the utilization of wearable wireless components. However, due to the slight reproducibility challenges and unexpected reliability testing results, the properties of the silver electro-textile material need to be carefully studied before it can be used in wireless platforms.

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