Research Article

Towards Washable Electrotextile UHF RFID Tags: Reliability Study of Epoxy-Coated Copper Fabric Antennas

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We investigate the impact of washing on the performance of passive UHF RFID tags based on dipole antennas fabricated from copper fabric and coated with protective epoxy coating. Initially, the tags achieved read ranges of about 8 meters, under the European RFID emission regulation. To assess the impact of washing on the performance of the tags, they were washed repeatedly in a washing machine and measured after every washing cycle. Despite the reliability challenges related to mechanical stress, the used epoxy coating was found to be a promising coating for electrotextile tags in moist conditions.

1. Introduction

Wireless body area networks are an increasingly important area of research and the future expectations on wearable electronics are high [1–3]. For example, wearable RFID (radio-frequency identification) tags have enormous potential in future monitoring, welfare, and healthcare applications. In this study, antennas for wearable passive ultra-high-frequency (UHF) RFID tags were fabricated from commercially available copper fabric and coated with a protective epoxy layer. To evaluate the reliability of the tags, they were washed repeatedly in a household washing machine using a common 40°C washing program with detergent and spinning and tested wirelessly after each washing cycle. All the tags were washed at the same time in a single washing bag with no other laundry. The impact of washing on noncoated copper fabric was also tested by washing a sheet of copper fabric without any coating and using the washed fabric for the fabricating of tags.

The remainder of the text is organized as follows: Section 2 gives a short review of UHF RFID systems and shortly introduces the development of wearable antennas and RFID tags. Section 3 introduces our tag design and the fabrication of tags as well as the brush-painting of the

protective coating. The tag measurements are presented in Section 4. Section 5 presents and discusses the measurement results before and after washing and analyzes the tag failures. Section 6 summarizes the conclusions of this study.

2. Textile Antennas and RFID Tags

Passive RFID technology provides the automatic identification and tracking of items. This is achieved with battery-free remotely addressable electronic tags composed of an antenna and an integrated circuit (IC). The use of propagating electromagnetic waves in the UHF frequency range for powering and communicating with the passive tags enables rapid interrogation of a large number of tags through various media. In comparison to barcodes and chipless RFID tags, IC-enabled tags allow the data stored in them to be updated wirelessly at any time. Thanks to the energy-efficient mechanism of digitally modulated scattering utilized in the tag-to-reader wireless communication, the data can be read from the distance of several meters and specialized antennas can provide reading distances reaching 25 meters without an on-board energy source. This makes the battery-free passive tags promising candidates as sensing platforms and digital entities in Internet of Things [4].

For further information on RFID technology, we refer to landmark articles [5, 6] presenting early investigations and [7] which provides a comprehensive introduction to today's passive UHF RFID systems. A thorough discussion on antennas for RFID tags can be found in [8]. Until today, new applications based on the versatile RFID technology are continually emerging. In particular, the passive tags are promising candidates to provide energy-autonomous wireless sensors, which exhibit low complexity and cost [2, 4, 9, 10]. This makes them a promising technology for body area networks. Overall, this development is building upon and extending the great amount of research on wearable antennas conducted during the past decade. It commenced with the introduction of fully textile-based antennas for smart clothing [11–14] and was followed by numerous application examples, including FM radio reception [15], protective clothing for firefighters [16], and space suits [17].

Simultaneously, the high-frequency characterization of novel electrotexile materials provided insight on the attainable electromagnetic performance. Early investigations included electromagnetic characterization of transmission lines formed by embedding of metallic yarns into fabrics [18] and by screen printing of inks with metallic inclusions [19]. Further assessment on screen printing and investigation of stretchable screen printed conductors under tensile load was provided in articles [20, 21]. Characterization of electrotexiles based on conductive threads and metal coated fabrics specifically for wearable antennas was further discussed in articles [22, 23]. A look at the current state-of-the-art of embroidery and related manufacturing techniques is presented in publication [24].

Today, embroidery and metallized fabrics are commonly reported methods of creating antennas for wearable passive UHF RFID tags [9, 25–27]. Progress has also been made in inkjet-printing fabrication of antennas based on metal nanoparticle inks on leather [28] and fabrics [29–31]. RFID tag assembly based on direct write dispensing of screen printable silver and copper inks on textiles have also been presented [32, 33].

In addition to the assessment of the fitting mass manufacturing processes and materials, the robustness of textile antennas toward various environmental stresses, such as exposure to extreme climatic conditions [34] and mechanical stress, including stretching [35], crumpling [36], and bending [14, 37, 38], as well as absorption of moisture [39–41], is another major issue to be addressed before the large-scale deployment of body-worn antennas and RFID tags. Finally, machine washing [40, 42–46] has been established detrimental to the electrical performance of electrotexile devices, even with a limited number of wash repetitions. The challenge remains in identifying low-cost conformal coating materials that are compatible with textile materials and also meet the requirements of extremely low electromagnetic energy dissipation and mechanical durability. It should be noted that some commercial UHF RFID laundry tags are already available on the market, for example, Fujitsu WT-A522 UHF RFID Laundry Tag [47] and TAGSYS' LinTRAK UHF Tag [48].

FIGURE 1: Antenna geometry.

3. Fabrication and Coating of Tags

We chose the tags antennas to be T-matched dipoles with the structure shown in Figure 1. This is a very common class of antennas used in UHF RFID tags. In this work, the length (L) of the antenna was chosen to be 96 mm, which is similar to many commercial products and sufficient to avoid the ailments of electrically small antennas in the considered frequencies from 800 MHz to 1 GHz. The tag antennas were patterned from Less EMF Pure Copper Polyester Taffeta Fabric (Cat. #A1212) [49], which is a thin and lightweight fabric and can be easily cut with scissors. The sheet resistance of the fabric has been estimated as $0.4 \Omega/\text{Sq}$. The tag IC utilized in this experiment was NXP UCODE G2iL series IC [50], which has a low wake-up power of $15.8 \mu\text{W}$ (-18 dBm).

We modelled the tag IC and the copper fixture as a parallel connection of a resistance of $2.85 \text{ k}\Omega$ and capacitance of 0.91 pF , which represents the IC input at the wake-up power of the circuit [9]. In this work, we studied an antenna that achieved the complex-conjugate impedance matching with the chip around 970 MHz. This is somewhat higher than, for example, the centre frequencies of 866.5 MHz and 915 MHz specified for UHF RFID systems in Europe and North America, respectively, but it was chosen since in the future work these tags will be studied in the body-worn configuration where significant downward shift in operation frequency is expected due to the proximity of human body with high dielectric constant.

Normally, the read range of passive tags is limited by the forward link operation, that is, the efficiency of the wireless power transfer from the reader to the tag IC. Assuming free-space conditions for site-independent comparison, the attainable read range of the tag in the directions ϕ and θ of a spherical coordinate system with the tag in its origin is given by [8]

$$d_{\text{tag}}(\phi, \theta) = \frac{\lambda}{4\pi} \sqrt{\frac{\chi_{\text{pol}}(\phi, \theta) \tau e_r D(\phi, \theta) \text{EIRP}}{P_{\text{ic0}}}}; \quad (1)$$

$$\tau = \frac{4 \text{Re}(Z_{\text{ant}}) \text{Re}(Z_{\text{ic}})}{|Z_{\text{ant}} + Z_{\text{ic}}|^2},$$

where λ is the wavelength of the reader's carrier signal, EIRP is the regulated equivalent isotropic radiated power of the reader, P_{ic0} is the wake-up power of the tag IC, χ_{pol} is the mutual polarization power efficiency between the tag and reader antennas, e_r is the tag antenna radiation efficiency,

FIGURE 2: Simulated antenna-IC power transfer efficiency.

D is the tag antenna directivity, and τ is the antenna-IC power transfer efficiency determined by the antenna and IC impedances Z_{ant} and Z_{ic} , respectively. Equation (1) is a direct implication of Friis' simple transmission equation. Below we will report d_{tag} under the European RFID emission regulation: EIRP = 3.28 W, assuming aligned reader and tag antenna polarizations: $\chi_{\text{pol}} = 1$.

To provide insight on the nominal electromagnetic performance of the textile tag and to predict the impact of reduction in the antenna conductivity, we simulated the antenna using ANSYS HFSS version 15 (full-wave electromagnetic solver based on finite element method) with various sheet resistance values assigned for the conductor. The results, including a comparison with a tag based on an antenna made of 20 μm thick sheet of bulk copper, are presented in Figures 2–4.

The results show that, for low values of sheet resistance, τ peaks approximately at 970 MHz. For larger values, the peak disappears and the antenna becomes detuned. The extreme case of 16.9 Ω/Sq , less than 20% of the power captured by the antenna is delivered to the IC. This was observed to be mainly due to the increase in antenna resistance, but also due to the decrease in antenna reactance, although it became notable only for large values of sheet resistance, 7.11 Ω/Sq and beyond. Figure 3 shows the impact of sheet resistance on the antenna radiation efficiency. Expectedly, it decreases with an increasing sheet resistance. However, at 970 MHz, the nominal sheet resistance of 0.4 Ω/Sq is still expected to provide e_r of more than 50%. From Figure 4, we can see that this performance translates to attainable read range of 8.5 meters at 970 MHz. In comparison to the tag with a bulk copper antenna, this is 4.2 meters less, but without a doubt sufficient for many applications of textile-based wearable systems.

The manufacturer had mounted the chip on a fixture with two $3 \times 3 \text{ mm}^2$ pads which we connected to the antenna

FIGURE 3: Simulated antenna radiation efficiency.

FIGURE 4: Simulated attainable read range of the tag.

terminals using conductive epoxy (Circuit Works CW2400). From our previous study, we knew that the copper electrotexile tags do not endure washing without a protective coating, as the noncoated copper fabric tag became dysfunctional after four wash repetitions in a study published in [42]. Thus, ESL 243 White epoxy coating [51] was applied by brush-painting it to cover the tags completely. The tags were coated on one side and dried for 40 minutes in 115°C, which was then

FIGURE 5: Noncoated (lower) and coated (upper) copper fabric tags.

repeated for the other side, so that the coating covered the whole tag. The long drying time and low drying temperature (recommendation from the coating manufacturer: drying in 125°C for 10–15 minutes and curing in 150°C for 5–15 minutes) were chosen because of the low temperature endurance of the tag IC. Only one layer of coating was used. After the drying of the coating, we shielded the area around the IC, using regular textile glue on top of the actual protective coating, in order to protect the IC and the IC-antenna joint from the mechanical stress during washing. Figure 5 shows a coated and a noncoated tag.

4. Wireless Measurements

We analyzed the performance of the assembled textile RFID tags based on the measured threshold power (P_{th}), which is the minimum output power of an RFID reader to activate the tag under test from a given distance. It can be measured using RFID readers and testers with adjustable output power. In this work, we have used Voyantic Tagformance measurement system [52] to conduct the measurement through a range of frequencies from 800 MHz to 1000 MHz. Because the measured threshold power depends on the measurement site and hardware, we used the attainable free-space read range of the tag (d_{tag}) derived from P_{th} to provide universal tag characterization. As detailed in article [35], we can estimate d_{tag} based on the measured threshold power of the tag under test and a system reference tag as

$$d_{tag} = \frac{\lambda}{4\pi} \sqrt{\frac{EIRP}{\Lambda} \frac{P_{th}^*}{P_{th}}}, \quad (2)$$

where Λ is a parameter (unit: watts) describing the sensitivity of the reference tag of the measurement system and P_{th}^* is the measured threshold power of the reference tag. In this paper, we report all the read range results under the European RFID emission regulation: $EIRP = 3.28$ W in the direction of the positive y -axis in Figure 1. In general, the yz -plane is the omnidirectional plane of the dipole antenna where the read range is approximately equal in all directions. In all measurements, the dipole tag was aligned for polarization matching with a linearly polarized reader antenna. Based on the calibration data provided by the manufacturer of the measurement system, we have estimated that the maximum variability in d_{tag} due to variability in the system reference tag (Λ) and the output power meter of the reader (P_{th} and P_{th}^*) is less than 5% throughout the studied frequency range.

FIGURE 6: Measurement results for a tag that is working well after 15 washing cycles.

5. Results and Discussion

The attainable read ranges based on threshold power measurement of coated copper electrotextile tags before and after washing cycles, in the frequency range of 800–1000 MHz, are presented in Figures 6–8. The tags were washed up to 15 times or until the read range had reduced below one meter, which was considered as a failure limit in our experiment. The results show that initially the epoxy-coated copper fabric tags achieved attainable peak read ranges of approximately 7–8.5 meters, within the frequency range from 960 MHz to 970 MHz.

It was noticed that the epoxy coating was well suited for shielding the tag from moisture and detergent. As can be seen in Figure 6, the peak read ranges after 15 washing cycles were still nearly 7 meters. The frequency of the peak read range had shifted to the frequency range 920–940 MHz, but as seen from Figure 6, this happened already during the first 5 washing cycles and no further frequency-shift or decrease in the read range was observed after that.

However, it was discovered that the mechanical stress during washing can seriously affect the tags' performance. Some tags stopped working after the first washing cycle, even though they worked fine after the coating. After studying the broken tags, it was found that the IC fixture pads remained well attached to the antenna, but the IC itself had been ripped off and remained attached to the coating material. The IC fixture of a broken tag is shown in Figure 9. The IC was most likely attached to the coating when it was brushed over the IC fixture and dried and was ripped off from the fixture

FIGURE 7: Measurement results for a tag where the read range was steadily decreasing after each washing cycle.

FIGURE 8: Measurement results for a tag where the peak read range was found to strongly shift to lower frequencies after each washing cycle.

FIGURE 9: The IC fixture of a broken tag; the IC has been ripped off from the IC fixture and attached to the coating material; magnification is $\times 6.3$.

FIGURE 10: The attachment of the IC fixture pad to the antenna is open; magnification is $\times 20$.

because of the mechanical stress during washing, due to a stronger adhesion strength between the IC and the coating in comparison with the IC and the IC fixture. Thus, in order to protect the IC and IC-antenna joint from the mechanical stress during washing, instead of shielding the IC part with regular textile glue on top of the actual coating, the IC and the IC-antenna joint should be shielded with a flexible material already before applying the actual coating.

For all tags, a downward shift in the frequency of the peak read range was observed after 3–5 washing cycles. After this, the read range of some tags started to steadily decrease after each washing cycle (see Figure 7). For other tags, the peak read range was found to not only slightly decrease, to about 7 meters, but to also strongly shift to lower frequencies after each washing cycle. This is seen in Figure 8, where after 15 washing cycles the frequency of the peak read range was between 880 MHz and 900 MHz. This shift in frequency and decrease in the read range may be an indication of gradual detachment of the IC. This was confirmed in our failure analysis. As shown in Figure 10, the IC fixture pad was found to be poorly attached to the antenna, most probably because of the strong mechanical stress during washing and spinning. Another reason behind the decreased read range can also be the cracking of the protective coating, again caused by mechanical stresses and deformation of the tag during washing. Examples of these cracks can be

FIGURE 11: Cracks in the protective coating; magnification of the tags is $\times 12.5$.

seen in Figure 11. Even though the coating is protecting the antenna from moisture, these stress-related cracks allow the moisture to penetrate the antenna under the coating, causing a detrimental impact on the tag performance.

The impact of washing on noncoated copper fabric was also tested by washing a piece of fabric 15 times without any coating and using the washed fabric for fabricating tags. None of the fabricated tags worked, which supports the results of our earlier study [42], where it was noticed that the copper fabric is not washable without a protective coating. The epoxy coating used in this study protects textile tags from water and detergent but does not provide sufficient protection against the strong mechanical stress from washing and spinning.

Some initial washing tests for electrotexile RFID tags with acrylic coating, some epoxy coatings, textile glue, and also some silicone materials have been published [42, 43]. In our future research, besides epoxy materials, potential coating materials also include different types of silicone materials, and DuPont's PE772 [53], stretchable protective encapsulant for wearables. After these preliminary washing tests, conditions defined in standardized tests for textiles for domestic uses will be addressed [54]. In addition, on-body measurements and optimization of the antenna to be used near the body are important future topics.

6. Conclusions

Textile antennas enable seamlessly integrated wearable RFID tags and other wireless devices in body area networks, where new applications are continually emerging. We studied the impact of washing on epoxy-coated copper fabric textile UHF RFID tags. Tag samples were washed in a household washing

machine, in a 40°C washing program with detergent and spinning, and tested wirelessly after each washing cycle.

Initially the epoxy-coated tags achieved attainable peak read ranges of approximately 8 meters. The tags maintained read ranges of 7 meters after 15 wash repetitions, which is very promising for future wearable applications. However, strong mechanical stress during washing and spinning was found to cause a major damaging impact on tag performance. In addition, the IC needs to be shielded with a flexible coating, which does not attach to the IC, before applying the actual coating.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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