The Possibilities of Embroidered Passive UHF RFID Textile Tags as Wearable Moisture Sensors

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Abstract—Moisture measurements of the body can be used for healthcare purposes as well as for helping in exercising. In this paper, the suitability of passive UHF RFID technology for moisture sensing is investigated. The technology has a great potential in wearable, comfortable, and wireless moisture sensing systems, although it is not originally used for sensing purposes. In our study, the tag antenna outlines are embroidered on a fabric substrate, the tag ICs are attached by embroidery or with conductive glue, and the tag performance as a moisture sensor is evaluated by wireless measurements. All tags attained peak read ranges of about 7-8 meters, which is well enough for wireless moisture sensors. The effects of moisture on the tag response were noticeable through a frequency range of 900-980 MHz and the tag performance was excellent also when wet. Thus, the achieved results indicate high potential of passive UHF RFID textile tags in moisture sensing and embroidery as a textile tag antenna and antenna-IC interconnection fabrication method.

Keywords—embroidery; fabric antennas; moisture; passive sensing; UHF RFID; wearable technology; welfare technology

I. INTRODUCTION

Passive wearable sensors are a major step in the development of future body-monitoring networks and are thus a growing area of research [1][2]. Future wearable sensors allow remote monitoring of patients or for example give feedback from physiotherapy exercises. Especially passive wearable humidity sensors have versatile applications: They are of great importance in several sectors, including sports and healthcare, as they enable biological fluids, such as human sweat or urine, to be continuously monitored [3]. Many physiological and metabolic functions are affected by an individual’s hydration status, and thus sweat rate can be used to estimate body hydration and how much fluid is needed. In wound healing monitoring, real-time moisture measurements will provide an indication when to replace the dressing. Also the basic problem of keeping checking whether a diaper needs changing can be avoided by wireless moisture sensors. In addition, certain diseases and seizures cause sweating, and can thus be immediately noticed with the help of a wearable moisture sensor [4][5]. Moisture monitoring sensors integrated into textile materials are not only innovative but they also represent the first attempt to use such an idea in a system that will be worn directly on the body [3].

One technology with a huge potential in future wearable sensing applications is passive UHF (ultra high frequency) RFID (radiofrequency identification) technology. The battery-free, remotely assessable electronic tags are composed of an antenna and an integrated circuit (IC), and can be read from distances of several meters. It is possible to establish maintenance free sensors without external sensors or onboard electronics by using a passive UHF RFID tag antenna as the sensing element [1][2]. Antenna-based sensing provides integration of sensing capabilities into passive RFID tags with a minimal increase in the overall complexity and power consumption of the tag: the RFID tag’s response can be manipulated according to the prevailing circumstances, such as presence of certain materials, e.g., water. The changes in the antenna or antenna substrate affect the impedance matching of the tag antenna and the tag IC, as well as the gain of the tag antenna. Through these they also affect the wirelessly measurable parameters and make these passive tags highly suitable to act as passive sensors. These types of simple tags can be also integrated into clothes for wireless wearable sensors.

Embroidery using conductive yarn is one highly potential additive textile RFID tag fabrication method. Sewing is a simple manufacturing method with great possibilities due to its compatibility with various textile materials [6]-[11]. In embroidery, it is possible to control the whole conductive pattern: outline, stitch density, and stitch type. The effects of the sewing pattern on RFID tag’s wireless performance have been studied in [7]. It has been shown that the conductivity of a sewed antenna depends on the electrical properties of the conductive yarn, the structure of the sewed pattern, and stitch and thread density of the sewed pattern. In addition to conductor and antenna fabrication, sewing has also been found to be a highly potential method for embedding electrical interconnections into textile materials [6]-[11]. However, to the best of our knowledge, this is the first study of embroidered RFID tag antennas as sensors, more precisely as textile-based moisture sensors.

In this paper, we present passive UHF RFID tags with simple and cost-effective embroidered contour antennas, together with sewed and glued antenna-IC interconnections, and test their suitability to act as textile-based moisture sensors.
II. TAG FABRICATION

The studied tag antenna geometry (shown in Fig. 1) is a straight dipole, which is a widely used antenna type in UHF RFID tags. This antenna originates from a strain reliability study of stretchable electro-textile and screen-printed tags [12]. The dimensions of the tag antenna (2 cm x 10 cm) are close to many commercial tag antennas.

![Geometrical parameters in millimeters.](image)

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<thead>
<tr>
<th>L</th>
<th>W</th>
<th>a</th>
<th>b</th>
<th>c</th>
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<tbody>
<tr>
<td>100</td>
<td>20</td>
<td>14.3</td>
<td>8.125</td>
<td>2</td>
</tr>
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Fig. 1. The tag antenna geometry.

The tag antennas were fabricated on a stretchable textile material that is a mixture of viscose and polyester. The used thread is multifilament silver plated thread (Shieldex multifilament thread 110f34 dtx 2-ply HC). The DC lineal resistivity of the thread is $500\pm 100\ \Omega/m$, and the diameter is approximately 0.16 mm. In our study, only the borders, i.e., the contour of the antenna was sewed, and two rounds of stitches were used. Significant amounts of time and conductive yarn can be saved in RFID tag antenna fabrication by only partially sewing the tag antenna.

The tag chip we used was NXP UCODE G2iL series RFID IC with the wake-up power of $-18$ dBm (15.8 µW). It was provided by the manufacturer in a fixture patterned from copper on a plastic film (See Fig. 2 for the IC fixture). We attached the fixture copper pads to the antennas by embroidering one round of contour under them and then one round on top of them with the conductive yarn during antenna fabrication. Thus, we were able to fabricate the antenna and antenna-IC interconnection at the same time with the same fabrication method. Finally, for comparison, we created another set of identical tags where the IC was attached by using conductive epoxy (Circuit Works CW2400).

![Fig. 2. The used IC strap.](image)

The ready-made tags with glued and sewed antenna-IC interconnections are shown in Fig. 3, and for both tag types, we fabricated 3 tags.

Fig. 3. A ready RFID tag (top) and glued (bottom left) and sewed (bottom right) antenna-IC interconnections.

III. MEASUREMENTS

In this work, we focused on evaluating the performance of the fabricated passive moisture sensor tags in air, in absence of any other environmental stress factors than moisture, and the effects of the proximity of the human body on wearable tags. Thus, the source of any observed performance variation is limited to the antenna-IC interconnection fabrication method and to the effects of moisture.

The response from the passive RFID tag is affected by the prevailing circumstances and surrounding materials. In case of a passive textile-based humidity sensor tag, the response of the tag as a function of increased humidity is measured. The increased moisture will change the permittivity of the fabric substrate, and thus change the impedance of the antenna, which will create a mismatch between the tag antenna and the tag IC. The increased moisture will also usually increase the losses in the fabric substrate, degrading the overall tag performance. That is, the humidity will cause a degradation of the tag performance, enabling the antenna-based sensing of humidity. However, the moisture may also lower the ohmic losses in the antenna pattern, since drinking water also contains some ions (conductivity of 0.005 – 0.05 S/m) [13], although its effect is assumed to be minor.

The tags were tested wirelessly using Voyantic Tagformance Lite measurement system. The system is formed of 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 (as low as $-80$ dBm) from the tag under test. The performance of the tags was examined dry, wet, and after drying them again.

In our measurements, the power on tag and the tag read range were measured. The power on tag (in dBm) is the transmitted threshold power normalized by the power loss factor (path loss) from the source output port of the generator.
to the antenna port of a 0 dBi antenna. This means that the power on tag is the threshold power multiplied by the power loss factor. It is the minimum power necessary to activate the chip, assuming 0 dBi tag antenna gain and perfect matching. The normalization of the transmitted threshold power makes it possible to compare the tag antennas consistently. The read range is simply the reading distance of the tag from the reader (in m).

During the test, we recorded the lowest continuous-wave transmission power (i.e. the threshold power $P_{th}$) at which the passive tag remained responsive. The wireless channel from the reader antenna to the location of the tag under test was characterized using a system reference tag with known properties. As explained in [12], this enables the estimation of the attainable range of the tag ($d_{tag}$) versus frequency from

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

where $\lambda$ is the wavelength of the transmitted signal from the reader antenna, $P_{th}$ is the measured threshold power of the sensor tag, $\Lambda$ is a known constant describing the sensitivity of the system reference tag. $P_{th*}$ 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 in European countries.

IV. RESULTS AND DISCUSSION

The initial read ranges of the fabricated 3 tags with sewed and 3 tags with glued antenna-IC interconnections are presented in Fig. 4 in the frequency range of 800-1000 MHz. As can be seen from Fig. 4, initially all tags achieved peak read ranges of about 7-8 meters, which is well enough for wireless moisture sensors. The peak read ranges are achieved at around 920-940 MHz and there are small variations in the peak read range frequencies, especially the tags with the sewed interconnections seem to be working at a slightly lower frequency. In general, however, the reproducibility can be considered to be quite good, already at this prototype stage. In addition, the results are very close to the ones firstly presented with this antenna fully fabricated from electro-textiles and by screen printing the antenna geometry on a fabric substrate: the electro-textile tags achieved peak read ranges of almost 7 meters at the frequency range of 920-940 MHz and the screen-printed tags achieved peak ranges of 9.5 meters at a frequency of 930 MHz [12]. Thus, our tags with the embroidered contour antennas seem to be working in a similar way as the fully fabricated electro-textile and screen-printed tags. However, with our fabrication method, a significant amount of material can be saved by only partially fabricating the antenna from conductive yarn.

After the initial measurements, the tags were wetted by spraying water on them from a spray bottle and measured again. After the second measurements, the tags were dried in normal office room conditions for about 48 hours and measured for the third time.

The tags were also weighted at their initial stage, when wet, and when they were dry again. The accuracy of the weight measurement was 0.0001 g and the results of these weight measurements are shown in Table 1. Here we present the results for the two tags out of the six tags that were chosen to present a tag with a sewed interconnection and a tag with a glued interconnection in this paper. As can be seen, the increase of weight was between 104-120 %, which means that the tags were completely wet. After drying for 48 hours, the weight returned close to the initial value, as was expected.

TABLE I. Weight measurements.

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<tr>
<th></th>
<th>Initial</th>
<th>Wet</th>
<th>Dried</th>
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<tr>
<td>Sewed</td>
<td>1.498</td>
<td>3.065</td>
<td>1.497</td>
</tr>
<tr>
<td>Glued</td>
<td>1.203</td>
<td>2.743</td>
<td>1.202</td>
</tr>
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</table>

The read range results of the moisture sensor tag as dry, wet, and dry again, are shown for the tag with a sewed antenna-IC interconnection and the tag with a glued antenna-IC interconnection in Fig. 5. As can be seen, when wet, the peak read ranges of the tags are about 1-1.5 meters shorter than initially. Thus, also these read ranges are still suitable for moisture sensor applications and the tags can be considered to work very well also when wet. After drying, the read ranges of both tag types returned back to their original values.

The power on tag measurement results as dry, wet, and dry again for the tags with sewed and glued interconnections are presented in Fig 6. As can be seen, the difference in tag response (power on tag) is noticeable throughout 900-980 MHz frequency range, which means that it is possible to read from the tag response that the tag is wet. However, the sensor tags could be optimized for the readout with an RFID reader operating in a fixed regionally regulated frequency band.

According to our measurement results, the moisture content of the substrate fabric affected the passive UHF RFID tag performance, which means that these tags are suitable to be used as moisture sensors. The moisture did not prevent the tags from working very well, although the tag antenna...
impedance and the ohmic losses were affected by the moisture.

The sensor tags presented in this work are fully passive and do not need maintenance. In addition, the sensor tags also have all the functionalities of a normal passive RFID tag, which permits the use of several sensor tags in a small area, as they can be recognized using their unique identification codes. In addition to their use as sensors, these textile-based tags could be efficiently used, e.g., for patient identification, as they can be directly integrated into clothing.

However, a lot of work still necessary to investigate the effect of the human body on the measurement results, as well as to develop a reference/calibration system to eliminate the dependence of the measurement result on the distance and especially on the surrounding conditions. Also, the moisture should be absorbed in a more controlled way to make the measurement result more accurate. At this stage of the research, we can only tell whether there is moisture on the sample or not. In addition, in the future, calibration will be needed for different fluids due to differences in conductivity. Body fluids have significantly higher electrical conductivity compared to drinking water. However, promising results in passive UHF RFID sensing of sweat are already presented in [14], where electro-textile and screen-printed tag antennas were used as sweat sensors.

In this study, the embroidered tag antennas themselves were used as sensing elements, which due to its simplicity and good integration with fabric materials is a very suitable method for wearable applications. However, in the future, external sensors could also be used with the versatile UHF RFID technology, as new RFID ICs have I/O ports for external components.

V. CONCLUSIONS

In this paper, embroidered passive UHF RFID textile tags were tested as moisture sensors. The results indicate high potential of RFID technology in moisture sensing and also support the use of embroidery in tag antenna and antenna-IC interconnection fabrication. The next step is to study the use of these tags near the human body and optimize the antenna design for that purpose. Another future goal is to further develop the moisture sensing system in order to make more accurate moisture level measurements and measurements of other fluids.

ACKNOWLEDGMENT

This work was supported by the Academy of Finland.

REFERENCES


