Effects of Sewing Pattern on the Performance or Embroidered Dipole-Type RFID Tag Antennas

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***Abstract*— Embroidered tag antennas can be used in on-body applications, such as access control, human monitoring and sensor tag antennas. The objective of this paper is to investigate the performance of dipole-type tag antennas sewed with different thread densities and with two different sewing patterns. This paper shows that the performance of sewed dipole-type tag antennas improves, if the sewing pattern consists of sewed lines along the direction of current flow in the antenna. The sewed simple dipole which consists of sewed lines along the length of the dipole achieved up to 7.5 m read range in free space, which is comparable to the performance of the corresponding copper dipole.**

***Index Terms*—conductive thread, sewed tag antenna, wearable RFID, wearable tag antenna**

I. INTRODUCTION

RADIO frequency identification (RFID) technology enables identification and tracking of objects at high rates, without the need of line of sight and human interference. In this identification system, objects are tagged with transponders. The transponder consists of an antenna loaded with an integrated circuit (IC) which contains a unique identification code specified to the tagged object. Body-centric communication applications such as access control, human monitoring, and wireless sensor nodes require flexible, low-cost, wearable RFID tags. In addition, wearable tags should be integrated into clothing seamlessly. Embroidery techniques with conductive threads provide compelling means to achieve this [1]-[5].

Wearable tags are meant to be used near the body. Human body absorbs RF energy reducing the overall antenna performance. In this application, also humidity, bending and stretching likely affect the performance. However, in this study, we focused on evaluating the performance of sewed tags in air, in absence of environmental stress factors, so that the observed performance variations would be strictly due to the different sewing patterns.

A sewed antenna can be modeled as thick flat material with a distinct conductivity. Factors affecting the conductivity of sewed antennas are the electrical properties of the conductive thread, the sewing pattern, and the thread density [1, 2]. In [1] and [2], the performance of only T-matched dipoles sewed with one pattern is investigated. The purpose of this study is to explore the performance of two different dipole types (T-matched and simple) sewed with two different sewing patterns. Thus, this paper complements the results presented in [1, 2], and investigates the effect of the alignment of the threads in the structure of the sewed antenna on the performance of it.

II. THEORETICAL BACKGROUND

A sewed pattern can be considered as non-isotropic conductive material, since it has different conductivities depending on the direction of the current flow in the pattern and the place of measurement nodes. In addition, conductivity of a sewed antenna depends on the electrical properties of the conductive thread, the structure of the sewed pattern, and stitch and thread density of the sewed pattern [2]-[5].

Performance of a passive RFID tag is perhaps best described by its read range and realized gain. Read range (d_{tag}) is the maximum distance from which the reader manages to interrogate the tag and realized gain ($G_{r,tag}$) is the antenna gain (G_{tag}) multiplied with the antenna-IC power transfer efficiency (τ) describing the impedance mismatch loss at this component interface. Recalling that G_{tag} is the product of the antenna directivity and radiation efficiency, $G_{r,tag}$ presents the combined effect of all the key antenna performance parameters. In free space conditions,

$$G_{r,tag} = \tau G_{tag} \quad \text{and} \quad d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{\chi_{pol} G_{r,tag} EIRP}{P_{ic0}}}, \qquad (1)$$

respectively, where λ is the wavelength, χ_{pol} is the polarization mismatch factor between the tag and reader antennas, G_{tag} is tag antenna gain pointing towards the maximum reader antenna gain, $EIRP$ is the regulated isotropically radiated power, and P_{ic0} is the wake-up power of the tag IC. All the results presented in this paper are referred to polarization-matched case (χ_{pol}=1) and European emission regulations: $EIRP$ = 3.28 W.

During tag testing, we measured two quantities: the link loss factor (L_{iso}) and polarization-matched threshold power

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(P_{th}). Here L_{iso} is the ratio of the power received by a hypothetic polarization-matched isotropic antenna placed at the test location to the output power of the reader. P_{th} is the smallest power at the output of the reader which enables the tag under test to respond to EPCglobal UHF Class 1 Generation 2 *query* command (power delivered to the tag IC equals P_{ic0}) in a polarization-matched configuration. By the above definitions,

$$G_{r,tag}^{(m)} = \frac{P_{ic0}}{L_{iso} P_{th}} \quad \Rightarrow \quad d_{tag}^{(m)} = \frac{\lambda}{4\pi} \sqrt{\frac{\chi_{pol} EIRP}{L_{iso} P_{th}}}, \tag{2}$$

where we impose χ_{pol} =1 for comparison with the simulation results computed with equation (1). Here the superscript (m) marks the measured values.

In this paper, we characterize antennas primarily in terms of the simulated and measured read ranges computed with equations (1) and (2), respectively. However, since the compared tags are equipped with the same tag IC, the comparison of the realized gains yields the same conclusions.

III. Fabrication of the Embroidered Antennas

The embroidery tag antennas are sewed with computer aided embroidery machine, using cotton and the multifilament conductive thread Shieldex 110f34 dtex 2-ply HC [6]. Cotton is used as the substrate and the conductive thread is used in fabricating the antenna pattern. The tags are equipped with Alien Higgs-3 UHF RFID IC provided by the manufacturer in a strap fixture with large pads (Fig. 1). This facilitates the chip attachment on the textile material. The IC has the sensitivity of −18 dBm and an equivalent input parallel resistance and capacitance of 1500 Ω and 0.85 pF, respectively. The strap pads were attached to the antenna with conductive epoxy.

The electrical properties of cotton were measured using the resonance method [7]. The measured permittivity and loss tangent of dry cotton are 1.8 and 0.018, respectively. The used cotton textile has a thickness of 0.25mm. Simulations showed that presence of cotton does not affect the performance of the sewed dipoles. The reason is that the textile losses so small compared to the losses of the sewing thread. On the other hand, the used cotton textile is very thin, which also minimizes the effect of it on the performance of the sewed tags.

The used conductive thread has a weight of 110 dtex (dtex = g/10000m) raw yarn twisted with a second 110 dtex raw yarn to make a yarn of 220 dtex. Then the yarn is plated with silver to gain a weight of 275 dtex. Thus, the weight of silver in the thread is 55g/10000m (dtex). The DC lineal resistivity of the thread is 500±100 Ω/m, and the diameter is approximately 0.16 mm. The thread consists of 34 filaments in a yarn. Conductivity of the thread cannot be evaluated analytically, because it does not have a uniform conductive structure [2].

The fabrication process of the sewed antennas is rather simple and fast. First, the footprint pattern of the antenna is imported as an image file to the 5DTM Embroidery System software, which is installed on a computer. The stitching technique and stitch density used to embroider the antenna are controlled using the software. Finally, the ready-made stitch pattern file is uploaded to Husqvarna VIKING (Designer Ruby) computer aided embroidery machine, which embroiders the pattern automatically.

IV. Embroidered Simple Dipoles

First, using a finite-element method EM simulator, ANSYS HFSS, we have designed a copper-based reference dipole antenna, operating in UHF RFID frequencies (860-960 MHz). In the design process, the length of the dipole is adjusted to achieve inductive input impedance to conjugate-match the antenna to the capacitive IC. The designed geometry is then sewed with two different sewing patterns. Pattern 1 consists of sewed lines along the length of the dipole. Pattern 2 consists of a sewed line along the length of the dipole and zigzags sewed on top of it.

A. Effect of thread and stitch density on the performance of sewed antennas

In simulations, an embroidered dipole can be modeled as uniform conductor with a distinct conductivity and a thickness equal to the thickness of the upper face of the sewed pattern of the antenna [2]. This approach is also taken in the present work.

Moreover, the study [2] showed that the increase in the

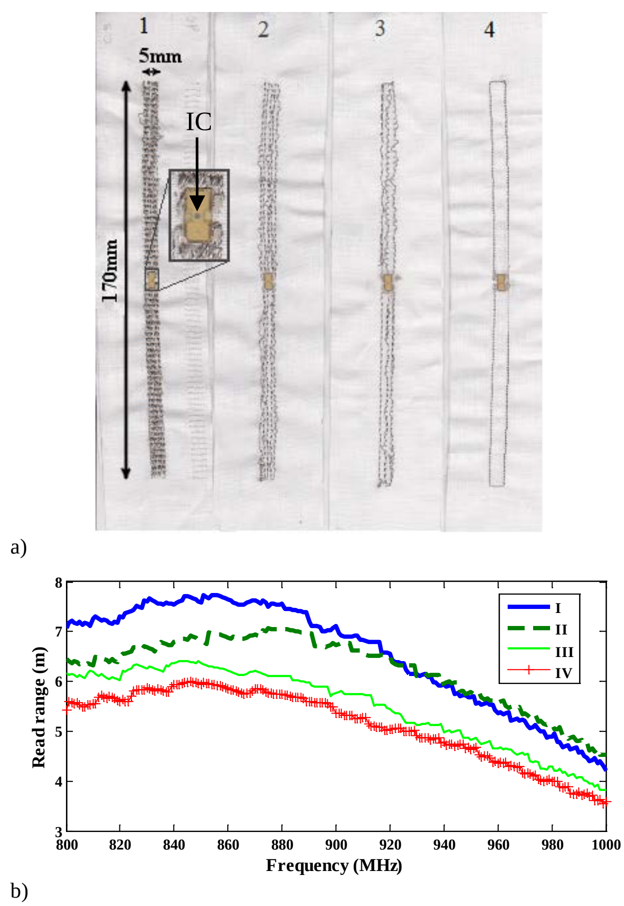


Fig. 1. Measured read ranges of sewed dipoles with Pattern 1 (see Fig. 2) with different thread densities. Dipole I has the highest thread density and the dipole IV has the lowest thread density.

thread density in the Pattern 2 did not improve the performance of the tag antenna. Thus, in the case of Pattern 2, we can neglect this parameter in the exploration of the effect of the sewing pattern on the performance of the antenna.

In order to find out the effect of the thread density on the performance of the dipoles sewed with Pattern 1, dipoles were fabricated with different thread densities (Fig. 1(a)). ICs were then attached to the antennas and the fully assembled tags were measured using Tagformance RFID measurement system, following the experimental procedure explained in Section II. Figure 1(b) shows the simulated and measured read ranges computed with equations (1) and (2), respectively.

As illustrated in Fig. 1(b), increasing the thread density of a dipole sewed with Pattern 1 improves the read range slightly. Thus, in contrast to Pattern 2, the thread density in Pattern 1 has an effect on the performance of the antenna.

B. Effect of sewing pattern on the performance of sewed simple dipoles

To explore the effect of the positions of the conductive threads in a sewing pattern on the performance of the antenna, we picked two embroidered simple dipoles with identical overall geometry, when each of them was sewed with a different sewing pattern. In addition, they have the same sewed conductive layer thickness. This allows for the fair comparison of the conductivities of the sewing patterns.

One of the subject dipoles is sewed with Pattern 1, and the other is sewed with Pattern 2 (Fig. 2(a)). The thickness of the upper face of both of them is measured as 0.2 mm. The effective conductivity of the sewed dipoles is then evaluated by searching a conductivity value for the simulation model of them. The conductivity value should derive simulations results which agree with the measurement results of the sewed dipoles. Figure 2(b) shows the measurement and simulation results.

As shown in Fig. 2(b), the maximum simulated read range moves to higher frequencies as the conductivity increases. Increasing conductivity affects the input impedance of the antenna and the impedance matching between the antenna and the IC. This shifts the antenna operating frequency to higher values. The dipole made of 0.05 mm thick copper layer has its maximum read range at approximately 900 MHz, while the maximum read range of the dipole sewed with Pattern 2 is approximately at 860 MHz.

The difference between the measurement and simulation results of the copper dipole seems to grow in frequencies out of the 860-960 MHz band. This is explained by the fact that the chip model used in the simulator is defined for the frequencies 860-960 MHz. Further uncertainty analysis showed that within this range, the difference between measurement can be explained by the combined effect of 7% variation in the antenna and IC impedances, antenna gain, and tag IC wake-up power. These variations are within the uncertainties of our simulation and test procedures.

According to Fig. 2(b), performance of the dipole sewed with Pattern 1 corresponds with the performance of the simulated dipole with a conductivity of 4000 S/m, and the

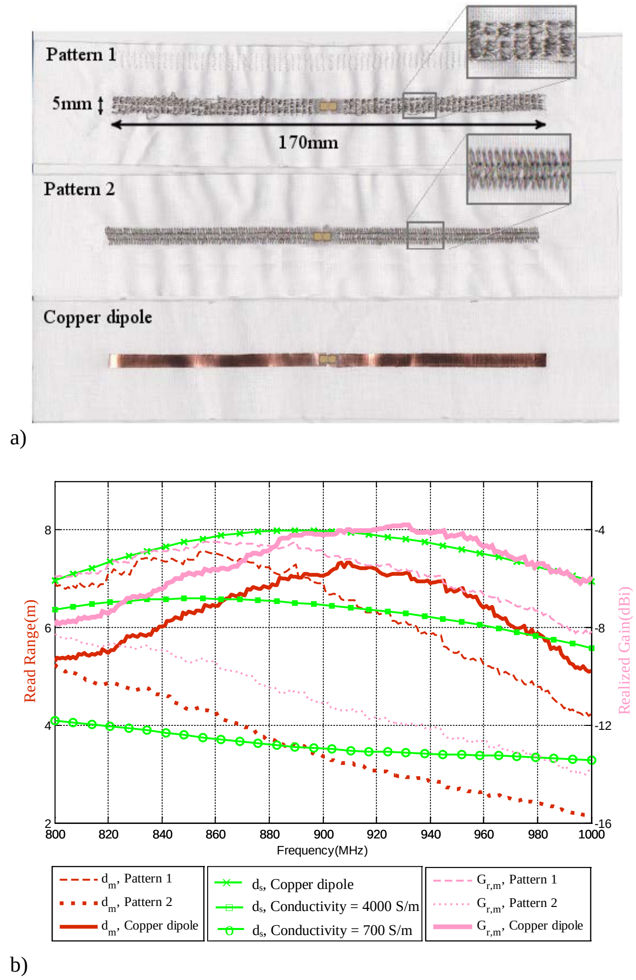


Fig. 2. (a) The upper dipole is sewed with Pattern 1, the dipole in the middle is sewed with Pattern 2, and the lowest one is a copper dipole, (b) measurement and simulation results of the dipoles shown in the picture.

performance of the simple dipole sewed with Pattern 2 corresponds with the performance of the simulated dipole with a conductivity of 700 S/m. Thus, in the case of simple dipoles, Pattern 1 has better performance and provides higher effective conductivity than Pattern 2. This result supports the findings reported in [3] and [8]: the conductivity increases if the sewing pattern consists of sewed lines in the direction of current flow.

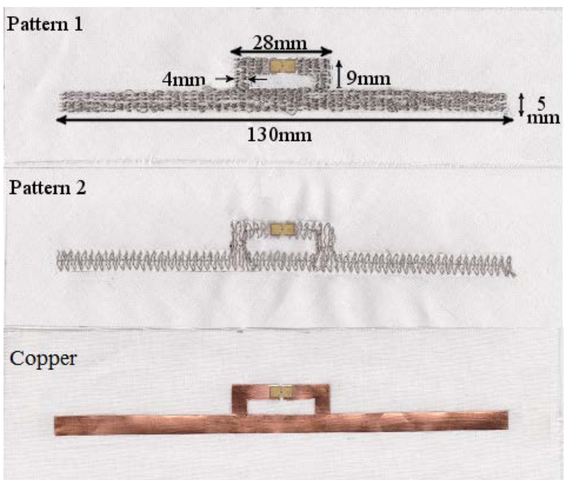
V. Sewed T-Matched Dipoles

In order to see whether Pattern 1 is always more conductive than Pattern 2, regardless of the antenna type, we fabricated two identical sewed T-matched dipoles with both patterns. Using a T-matching network, we can achieve a shorter dipole with inductive input impedance to conjugate-match the antenna to the capacitive IC. In RFID technology T-match network is a frequently used and known matching technique. Hence, it is important to explore it also in the case of embroidered tags.

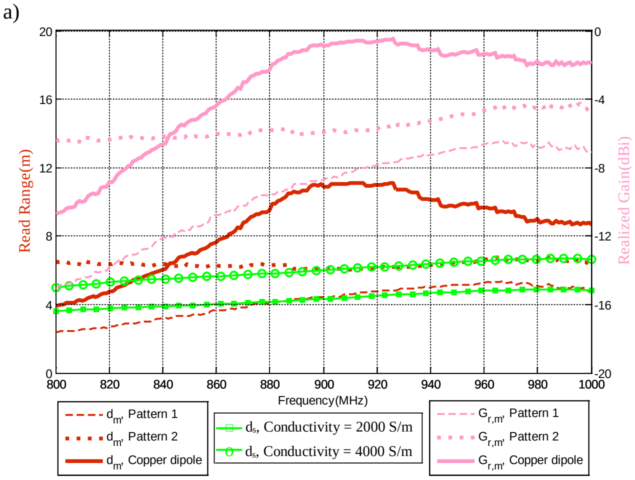
Figure 3(a) shows the fabricated T-matched dipoles.

Also in this case, first a copper dipole is designed to serve as a reference antenna. The designed geometry is then embroidered with both patterns; Pattern 1, and Pattern 2. The measured thickness of both of the sewed T-matched dipoles is 0.2 mm. Thus, any difference in the performance of the sewed T-matched dipoles is due to the different structure of the sewing patterns of them.

Similar to the case of simple dipoles, effective conductivity of each sewed T-matched dipole is evaluated using the simulation model of them. Hence, the effective conductivity of a sewed T-matched dipole is the conductivity that derives simulation results which agree with the measurement results of it. Figure 3(b) shows the measurement results of the sewed T-matched dipoles and the simulation results of the corresponding dipoles with conductivities 4000 S/m and 2000 S/m. As shown in Fig. 3(b), the T-matched dipole sewed with Pattern 2 has an effective conductivity of 4000 S/m and the dipole sewed with Pattern 1 has that of 2000 S/m. Thus, for the T-matched dipole, Pattern 2 achieves higher conductivity than Pattern 1. Apparently, the reason for the weakened performance of T-matched dipole sewed with Pattern 1 is the imperfect current flow in the vertical section of T-matching network. Consequently, in the design of embroidered antennas, we have to consider the direction of current flow in the whole antenna, and choose a sewing pattern which has conductive threads going along the current.



a)



b)

Fig. 3. (a) The upper T-matched dipole is sewed with Pattern 1, the dipole in the middle is sewed with Pattern 2, and the lowest one is a T-matched copper dipole, (b) measurement and simulation results of the dipoles shown in the picture.

VI. Conclusion

This paper investigates the effect of thread density and the relative positioning of the threads in a sewing pattern on the performance of sewed dipole-type tag antennas. Thread density affects slightly the performance of a dipole sewed with Pattern 1, which consists of only sewed lines along the length of the dipole. However, thread density does not significantly affect the performance of a dipole sewed with Pattern 2, which consists of a sewed line along the length of the dipole and zigzags sewed on top of it.

The simple dipole sewed with Pattern 1 achieves 7.5 m maximum read range in air, which is comparable to the maximum read range value of the corresponding copper dipole. The T-matched dipole sewed with pattern 2 achieves 7 m read range in air. In the case of T-matched dipoles, Pattern 2 provides better performance than Pattern 1. However, in the case of simple dipole, Pattern 1 has sewed lines along the direction of current flow resulting in higher effective conductivity and better read ranges. The reason for the weakened performance of the T-matched dipole sewed with Pattern 1 is the imperfect current flow in the vertical section of the T-matching network. Thus, when designing a sewing pattern, we must consider the direction of current flow in the whole antenna, and create a sewing pattern with conductive threads in the direction of current flow.

Knowing the factors affecting the conductivity of sewed dipoles, in the future we will optimize embroidered tags for operation in the vicinity of body. We will also investigate the effect of sewing pattern and thread density on the performance of other antenna types.

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