

# Characterization of Embroidered Dipole-type RFID Tag Antennas

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**Abstract**—Wearable RFID tags and wireless sensors can be used for on-body and human monitoring applications. Embroidery with conductive thread provides compelling means for the fabrication of seamlessly garment-integrable antennas for wearable tags and wireless sensors. In this paper, we present the fabrication of fully assembled tags based on embroidered dipole-type antennas. The prototype tags achieve 5.5-to-7 meters read range. Moreover, we present a method for estimating the effective conductivity of the embroidery pattern, which depends on the sewing pattern and the stitch density. This will enable the judicious optimization of embroidered tag antennas using electromagnetic simulation tools.

**Keywords**- conductive thread; embroidered RFID antenna; UHF RFID; sewing machine; wearable RFID tag

## I. INTRODUCTION

Radio Frequency Identification (RFID) system consists of a reader, and a remote transponder, denoted as a tag, which is attached to a labelled object. The tag is made of an antenna and a microchip containing the identification code related to the object. Passive tags provide the required energy to drive the microchip from the radio frequency wave transmitted by the reader antenna. In a passive RFID system, communication happens through backscattering modulation. Reader sends carrier wave to activate the tag and a command to backscatter the identification data. When the tag receives the command signal, the microchip switches its impedance between two values in a coded manner corresponding to the stored data during the reader's carrier signal phase. Thus, the tag scatters a modulated signal back to the reader. The reader then demodulates and decodes the signal and gives the data stored in the tag as output [1].

Wearable tags can be applied for youngsters, the aged, athletes and patients for the purpose of monitoring. Like all wearable antennas, they should be light weight, low cost, flexible, maintenance-free, and seamlessly integrated with clothing [2], [3]. Thus, embroidery with conductive threads is a compelling approach for the fabrication of such antennas.

Several flexible conductive materials have been introduced in literature, including fibers having polymer cores and metallic coatings (E-fibers) [4], [5], yarns bundled with thin metal filaments, yarns/fabrics embedded with carbon nanotubes [6],

and fabrics embedded with metal filaments [7]. In the referenced articles elastic polymers and fabrics have been used as the flexible substrate.

Tag antenna has a major role in the overall RFID system performance, such as the read range, and the compatibility with tagged objects. Wearable RFID tags have been designed and explored in [8]-[10]. Authors of these articles have sewed the geometry of the tag antenna on textile with a computer aided sewing machine using conductive threads. These articles explore the performance of sewed tag antennas, and investigate the factors affecting the conductivity of the sewed antennas. According to the measurement results of these articles the conductivity of sewed antenna improves by using highly conductive threads, increasing stitch and thread density, and also by choosing a sewing pattern that consists of sewed lines along the direction of current flow.

In this paper, we show that when designing an embroidery tag antenna, with electromagnetic simulators we can treat the complex embroidery pattern as a uniform conductive material layer when the pattern is sewed densely. Hence, it is the conductivity of an embroidery pattern that is the decisive factor in the simulation model of an embroidery antenna. This paper focuses on wearable embroidered dipole-type ultra high frequency (UHF) RFID tag antennas. The objective of this paper is to explain an estimation technique for the conductivity of sewed RFID tag antennas, and also to further investigate the factors affecting the conductivity and the performance of sewed dipole-type tag antennas. In this study the effects of human body and moisture in the cotton are not considered.

The rest of the paper is organized as follows. Section 2 explains the properties of the used materials, their effects on the performance of the antenna, and the fabricated prototypes. Section 3 discusses the measurement of the prototypes. Section 4 illustrates a modeling technique for the sewed dipole-type tag antennas. Finally, conclusions are drawn in Section 5.

## II. DESIGN AND FABRICATION OF EMBROIDERED ANTENNAS

In this article, we investigate the operation of dipole-type embroidery tag antennas, sewed on cotton, which is used as the substrate. Essential factors that define the operation of a planar

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antenna are the electrical properties of the substrate, electrical properties of the radiating element, and antenna geometry. The conductive thread used in the sewing of the antennas is Shieldex 110f34 dtex 2-ply HC [11].

At the beginning of this study, relative permittivity and loss tangent of cotton were unknown. Hence, the electrical properties of cotton are measured using the resonance method [12]. The measured relative permittivity and loss tangent of cotton (in dry condition) are 1.8 and 0.018, respectively.

The embroidery antennas are sewed with Husqvarna VIKING computer aided sewing machine, using conductive thread [11]. The 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. The DC lineal resistivity of the thread is  $500 \pm 100 \Omega/\text{m}$ , and the diameter is approximately 0.16 mm. The thread consists of 34 filaments in a yarn.

#### A. Electrical Properties of the Conductive Thread

Conduction losses of the radiating element of an antenna cause the antenna loss resistance to depend on the frequency. The high-frequency resistance of a metal structure is not the same as the DC resistance [13]. The DC resistance of a uniform metal rod with length  $l$  and cross-sectional area  $A$  is given by

$$R_{dc} = \frac{1}{\sigma} \frac{l}{A}, \quad (1)$$

where  $\sigma$  is the conductivity of the metal (S/m). When the frequency increases, the skin depth  $\delta$  ( $\delta = \sqrt{2/(\omega\mu\sigma)}$ ) becomes much smaller than the conductor radius and the current confines to a thin layer near the conductor surface. Hence, the high-frequency resistance, based on a uniform current distribution along the length of the rod, is given as [13]

$$R_{hf} = \frac{l}{P} R_s = \frac{l}{P} \sqrt{\frac{\omega\mu_0}{2\sigma}}, \quad (2)$$

where  $P$  is the perimeter of the cross section of the rod ( $P=2\pi b$  for a circular wire of radius  $b$ ),  $R_s$  is the conductor surface resistance ( $\Omega$ ),  $\omega$  is the angular frequency (rad/s),  $\mu_0$  is the permeability of free-space (H/m), and  $\sigma$  is the conductivity of the metal (S/m).

Equations (1) and (2) are defined for a uniform metal rod with a uniform current distribution. Conductive threads, however, do not have a uniform metal structure, and they consist of many filaments which are silver plated nylons. Thus, Equations (1) and (2) cannot be used to characterize the conductive threads. However, it is obvious that the conductivity of the conductive thread is higher the higher the weight of the metal part of the thread is. The weight of silver in the thread we have used is 55g/10000m (dtex), which provides a good conductivity.

In addition to the conductivity of the electric-thread, conductivity of the embroidery antennas depends also on the sewing pattern and the stitch density [8], [10]. Hence, at the first level, it is sufficient that the dtex value of the electric-

thread is high enough while the exact conductivity of the thread alone is less important for the antenna design.

#### B. Copper-based Reference Antenna

Conductivity of the radiating element of an antenna does not affect the operation frequency of the antenna directly, but it affects the quality factor ( $Q$ ) of the antenna: the higher the conductivity, the lower the  $Q$ . On the other hand, the relation between  $Q$  and the obtainable frequency bandwidth is defined as

$$\frac{\Delta f}{f_0} = \frac{1}{Q}, \quad (3)$$

where  $\Delta f$  is the frequency bandwidth and  $f_0$  is the center frequency. Thus, a decrease in the quality factor increases the obtainable frequency bandwidth of the antenna. Taking into account that copper has high conductivity, the copper-based reference antenna is likely to exhibit a narrower bandwidth compared with the embroidered antennas discussed in Section II.C.

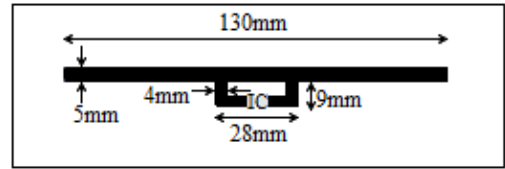


Figure 1. Geometry of the designed copper dipole-type tag antenna.

The dominant difference between a copper tag antenna and an embroidery tag antenna is their conductivities. Hence, in order to define an optimum geometry for a dipole-type tag antenna working in UHF region, we have designed a tag antenna consisting of copper as the radiating element, and cotton as the substrate. The geometry of the designed dipole is shown in Fig. 1. The thickness of the copper is 0.05 mm, and the dipole is designed for the chip, Alien Higgs-3 UHF RFID IC [14], which has a sensitivity of  $-18$  dBm. The chip has an equivalent input parallel resistance of  $1500 \Omega$ , and an equivalent input parallel capacitance of  $0.85$  pF. The chip is attached to the fabricated antenna with conductive epoxy [15].

#### C. Embroidered Antennas

The geometry of the designed copper dipole is sewed on cotton using the embroidery machine Husqvarna Viking. First the image of the antenna is exported from the HFSS software and transferred to the 5D Embroidery System software. Using this software we have created the sewing pattern for the antenna. The software enables to control the stitching techniques and the stitching density when creating the sewing pattern. The file containing the created pattern is then transferred to the embroidery machine to be sewed on cotton automatically. The created sewing pattern consists of a horizontal line along the length of the dipole, and zigzags sewed vertically on it.

Effect of the stitch and zigzag density on the performance of the antenna is investigated by sewing six dipoles with different zigzag densities and measuring them in an anechoic chamber. The fully assembled tags are shown in Fig. 2 with the amount of stitches of each sewed tag written on top of it. The dipole with 2550 stitches has the highest zigzag density, and the dipole with 225 stitches has the lowest zigzag density. The right-most tag is the copper-based reference.

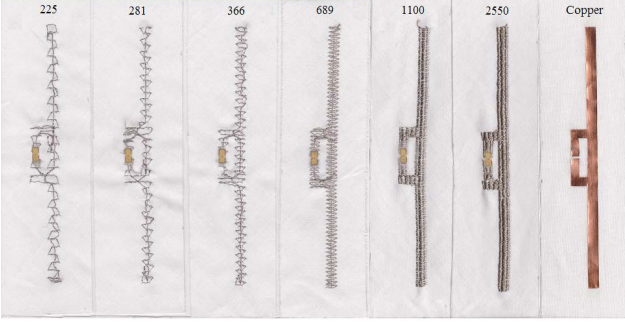


Figure 2. Sewed tags with different stitch densities.

### III. PERFORMANCE OF THE EMBROIDERED ANTENNAS

According to the articles [8] and [10], conductivity of an embroidery antenna increases as the thread and stitch densities increase. In our case, this means that increasing the zigzag density should increase the conductivity of the antenna.

To characterize the performance of the sewed dipoles, we have measured the achievable read range ( $r_{max}$ ) of the fully-assembled tags using RFID measurement system [16]. In practice the read range  $r_{max}$  is attained when the tag is located in the main beam of a reader antenna, which has its polarization perfectly aligned with the tag and is transmitting the maximum power allowed by the regulations. In our measurement configuration, the achievable read range is calculated as

$$r_{max} = \frac{\lambda}{4\pi} \sqrt{\frac{EIRP}{L_{fwd} P_{th}}}, \quad (4)$$

where  $\lambda$  is wavelength,  $L_{fwd}$  is the measured linkloss factor from the output port of the generator to the input of a hypothetical isotropic radiator placed at the tag's location,  $P_{th}$  is the minimum transmitted power required to turn the tag IC on, and  $EIRP$  is the regulated effective isotropic radiated power (EIRP). By definition,  $EIRP$  is the amount of power that would be needed to put into an isotropic antenna to produce the same power density in the radiation field as we get in the main beam of the directional antenna. In the European RFID band (865.7-867.6 MHz)  $EIRP = 3.28$  W.

Figure 3 shows the measured read ranges of the tags shown in Fig. 2. Comparing the read range graphs of the copper dipole with the corresponding graphs of sewed dipoles, we can observe that in the case of sewed dipoles the frequency bandwidth is greatly increased. This is mainly due to the reduction of conductivity and quality factor of the sewed antennas. The achieved read ranges of the sewed tags range

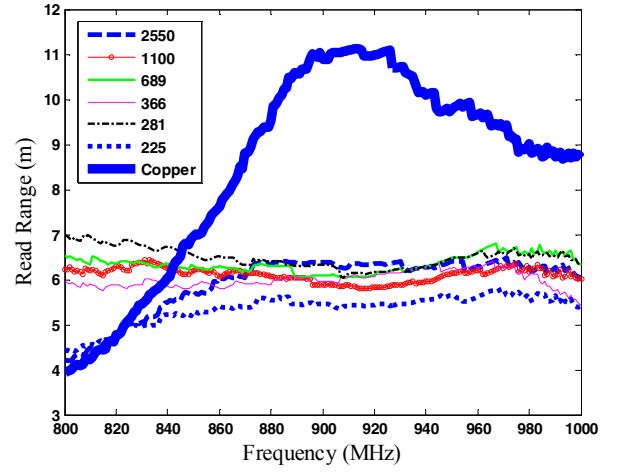


Figure 3. Measured forward read range graphs of sewed dipoles with different stitch densities

from 5.5 m to 7 m. This achievement is better than the results reported in [8]-[10] and without a doubt sufficient in many applications.

According to Fig. 3, performance of the sewed tags with this sewing pattern is fairly similar regardless of the zigzag density and only when the amount of stitches is as low as 225 the performance starts to change noticeably. Thus, it can be deduced that we can sew antennas with this sewing pattern sparsely to save materials and still achieve nearly as good performance as with antennas sewed with a high stitch and zigzag density. However, adding sewed lines along the direction of current flow might affect the conductivity of the antenna. But in this case, the sewing pattern will change significantly, and the resulting pattern might have even lower effective conductivity.

### IV. SIMULATION MODEL FOR THE EMBROIDERED ANTENNAS

For modelling the embroidery tag antennas, the effective conductivity of the embroidery pattern needs to be known. In this way the antenna can be modelled as a uniform conductor layer and its performance can be optimized in an appropriate manner. This section presents a technique to evaluate the conductivity of sewed antennas based on the comparison between simulation and measurement results. This enables the design of antennas optimized for a given stitch pattern.

#### A. Conductivity of Sewed Tag Antennas

One of the most important antenna parameters is realized gain of an antenna. Theoretically, the realized gain is a parameter that beside the directivity and efficiency of the antenna, accounts for the impedance matching between the antenna and the IC. Thus, the simulator calculates realized gain as

$$G_{r,s} = \tau G = \frac{4R_{IC} R_{ant}}{|Z_{ant} + Z_{IC}|^2} \times G, \quad (5)$$

where  $\tau$  is power transfer coefficient,  $R_{ant}$  is resistance of the tag antenna at its terminals,  $Z_{ant}$  is impedance of the tag antenna

at its terminals,  $R_{IC}$  is input resistance of the IC,  $Z_{IC}$  is the input impedance of the IC, and  $G$  is gain of the antenna. On the other hand, in empty-space measurement conditions, realized gain is defined as

$$G_{r,m} = \frac{P_{IC,sens}}{L_{fwd} P_{th}}, \tag{6}$$

where  $P_{IC,sens}$  is the sensitivity of the IC.

In order to find the conductivity of the sewed antennas, the measured realized gain graphs of the sewed antennas are compared with simulation results of the dipole with different conductivity values and thicknesses. In other words, measured realized gain  $G_{r,m}$  is compared with simulated realized gain  $G_{r,s}$ .

The thickness of embroidered antennas changes as a function of stitch density. When the amount of stitches and the thread density are high enough, in a sense that the sewed structure resembles a flat pattern, we can talk about the thickness of the sewed structure. But, when the sewed pattern is sparse, it is not convenient to talk about the thickness of it, because the sewed structure is not flat and solid. Still, in simulator we may to define a thickness for the antenna material. Thus, the thickness of the sewed structure on the upper face of each tag is measured, and it is defined as the thickness of the conductive part of the antenna in ANSYS HFSS simulator. The measured thicknesses of the sewed planar dipoles are listed in Table 1.

TABLE I. THICKNESS OF THE SEWED ANTENNA ON THE UPPER FACE OF EACH TAG

|                    |       |           |               |
|--------------------|-------|-----------|---------------|
| Number of stitches | 2550  | 1100, 689 | 366, 281, 225 |
| Thickness (mm)     | 0.425 | 0.2       | 0.1           |

As illustrated in Fig. 3, the read range graphs of sewed dipoles are located closely to each other. This might lead to a conclusion that the conductivities of sewed antennas are almost the same too. However, when we consider the thickness of the sewed structure, we end up with different effective conductivity values for each of them.

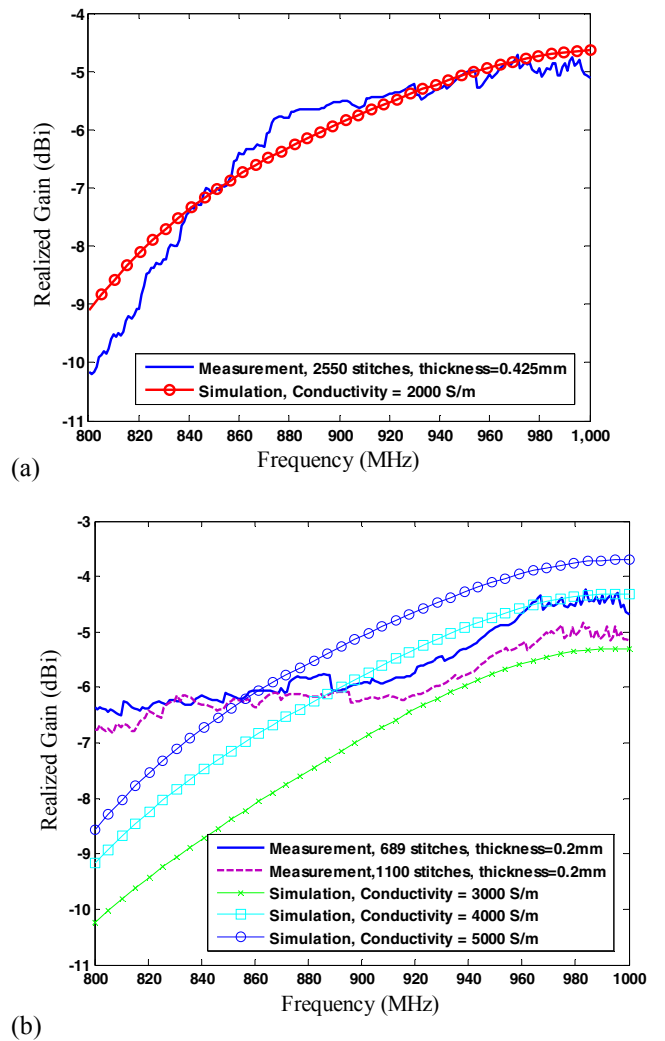
Conductivity of antenna affects the loss resistance of the antenna (3), which in turn affects the power transfer coefficient and the efficiency of the antenna. On the other hand, in equation (4),  $P_{th}$  is a function of the impedance mismatch between the antenna and the IC, and the conductivity of the antenna. Here, we model the sewed antennas, using the hypothesis that an antenna with a measured realized gain of  $G_{r,m}$  has the same conductivity as corresponding simulated antenna with a realized gain of  $G_{r,s}$ , when  $G_{r,s}$  is equal to  $G_{r,m}$ .

In this study, the only differences between the copper-fabricated and embroidered tags were the conductivity and thickness of the antenna conductor. Both of these parameters affect the antenna input impedance, but since the studied

antennas are otherwise identical, the possible variations in the input impedance can be modelled by varying only the conductivity and the thickness of the antenna conductor in the simulations. Therefore this effect is fully included in the realized gains analyzed in this study.

As it is shown in Fig. 4(a), the simulated realized gain of the dipole with a thickness of 0.425 mm and a conductivity of 2000 S/m matches with the measured realized gain of the sewed dipole with 2550 stitches. Thus, we can deduce that the conductivity of this sewed dipole is 2000 S/m.

Similarly, Fig. 4 (b) shows simulated realized gain of the dipole with different conductivities, and measured realized gain of sewed dipoles with 1100 and 689 stitches. In this case, in simulations the thickness of the dipoles is set to 0.2 mm. According to the Fig. 4 (b), the conductivity of sewed dipoles with 1100 and 689 stitches varies from 3000 S/m to 5000 S/m. Figure 4 (c) shows simulation results and measurement results of sewed tag antennas with 366, 281 and 225 stitches. In this case, in HFSS model the thickness of the dipole is 0.1 mm, which results in higher conductivity values. According to this figure the conductivity of these tag antennas varies from 6000 S/m to 10000 S/m.



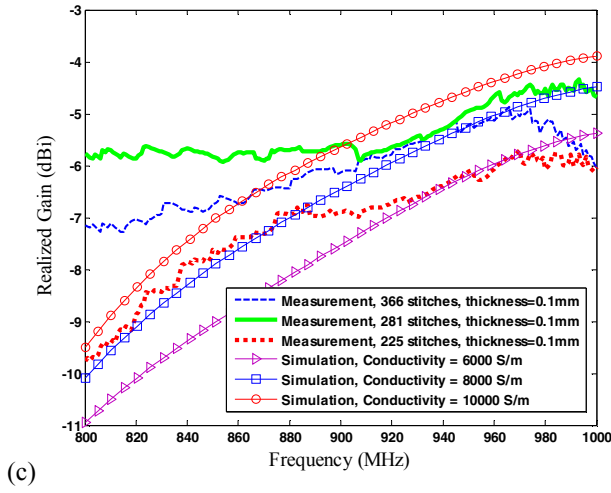


Figure 4. Measured realized gain graphs of sewed dipoles and simulated realized gains.

According to the presented results, the effective conductivity of the sewed dipoles decreases as the thread density and the thickness of the sewed pattern increases. There is little performance deviation between the sewed dipoles with 281-2550 stitches, while they have different thicknesses. Thus, the thicker and more densely sewed pattern (or conductive layer) must have smaller effective conductivity in order to have losses at the same level as the thinner one. In the densely sewed patterns, a larger amount of vertically sewed conductive threads are very close to each other and their interaction may cause unexpected losses compared to less dense sewing patterns.

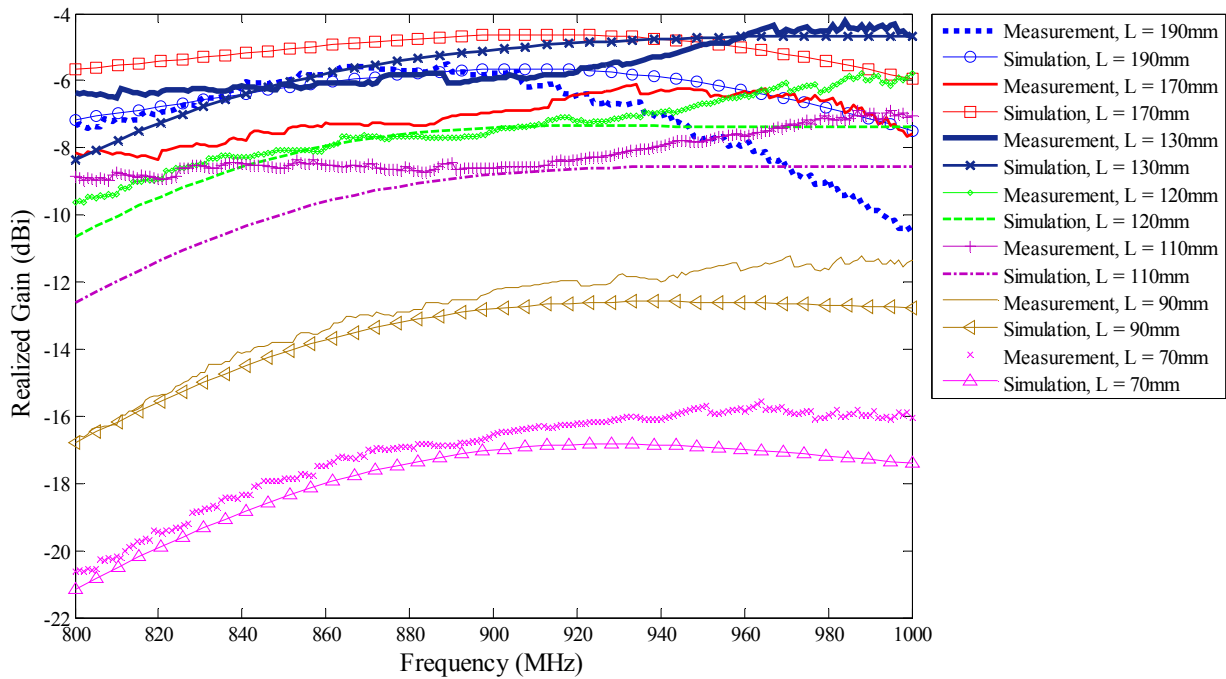


Figure 6. Measurement and simulation results of sewed dipoles with different lengths.

## B. Verifying the Simulation Model

In order to verify the proposed simulation model, six dipoles with six different lengths are sewed and measured. The sewed dipoles have the same zigzag density as the 130 mm long dipole with 689 stitches. Thus, the thickness and conductivity of all of them are 0.2 mm and 4000 S/m respectively (Fig. 4(b)). Figure 5 shows the picture of the sewed tag antennas.



Figure 5. Sewed antennas with the same T-match geometry as before, but with different lengths.

The in-air measurement results of the sewed dipoles are then compared with the simulation results of them. As Fig. 6 shows, the measurement and simulation results of most of sewed dipoles match quite well. According to the datasheet of the IC [14], sensitivity of the IC is -18 dBm at frequencies 860-960 MHz, but the simulator use this value in its calculations in the whole frequency area (800-1000 MHz). In addition, the simulator uses a circuit model for the IC, which is also defined

for the frequencies 860-960 MHz. Thus, the reason for the slight difference in simulation and measurement results outside this frequency area could be the possible change of the sensitivity of the IC, and the imperfectness of the circuit model at lower frequencies than 860 MHz and higher frequencies than 960 MHz. Another reason for the slight difference is that sewed antennas are not made of homogeneous conductive material as they are modelled in the simulator.

Figure 6 proves the validity of the hypothesis and the modelling method explained in the previous subsection. This method is applicable in designing T-matched dipole-type embroidery tag antennas.

## V. CONCLUSIONS

Embroidered RFID tag antennas have been designed for UHF RFID applications. The designed dipoles are embroidered on cotton with different stitch densities. The sewing pattern consists of a sewed line along the length of the dipole, and zigzags sewed on it. The sewed dipoles are measured in anechoic chamber, when the cotton was dry. The measured read ranges of the sewed dipoles vary from 5.5 m to 7 m, offering excellent performance for many practical applications.

Conductivity of the sewed dipoles is estimated as a function of the thickness of the sewed structure. The evaluated conductivity values vary from 2000 S/m to 10000 S/m. According to the modelling technique presented in this paper, the overall conductivity of sewed antennas decreases as the thread density and the thickness of sewed structure increases. In the densely sewed patterns, a larger amount of vertically sewed conductive threads are very close to each other and their interaction may cause unexpected losses compared to less dense sewing patterns.

The evaluated conductivities of the sewed dipoles and the presented modelling technique can be used in future for optimization of the sewed antennas to operate in the vicinity of body.

According to the presented results, in the case of the sewing pattern presented in this paper, it is not necessary to sew T-matched dipole-type tag antennas with a high stitch and thread density. We can achieve high read range values even from very sparsely sewed T-matched dipoles, and thus achieving cost-savings by using less conductive threads and reducing the time spent on sewing.

In the future, it is important to further investigate the effect of the structure of the sewing pattern along with the geometry of the antenna on the conductivity of embroidery antennas. Conductivity of a sewing pattern might be higher for distinct antenna geometries, and lower for some other antenna types. So, it is preferable to study more the relation between the sewing pattern and the antenna type or geometry. In the future, also the operation of sewed tag antennas can be explored more precisely by studying the effect of relative positioning of electric threads in a sewing pattern on the input impedance of the tag antenna. This could be done by comparing the measured input impedance of tag antennas, when they are sewed with different kinds of sewing patterns.

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