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PERFORMANCE STUDY OF SCREEN-PRINTED TEXTILE ANTENNAS AFTER REPEATED WASHING

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Abstract:

The stability of wearable textile antennas after 20 reference washing cycles was evaluated by measuring the reflection coefficient of different antenna prototypes. The prototypes' conductive parts were screen-printed on several textile substrates using two different silver-based conductive inks. The necessity of coating the antennas with a thermoplastic polyurethane (TPU) coating was investigated by comparing coated with uncoated antennas. It is shown that covering the antennas with the TPU layer not only protects the screen-printed conductive area but also prevents delamination of the multilayered textile fabric substrates, making the antennas washable for up to 20 cycles. Furthermore, it is proven that coating is not necessary for maintaining antenna operation and this up to 20 washing cycles. However, connector detachment caused by friction during the washing process was the main problem of antenna performance degradation. Hence, other flexible, durable methods should be developed for establishing a stable electrical connection.

Keywords:

Screen-printed textile antennas, conductive ink, textile, washing

1. Introduction

In the last decade, research into the development of flexible textile antennas increased significantly because of the promising integration possibilities into garments, resulting in wearable textile systems that can communicate wirelessly with a nearby base-station. The deployment of such systems is beneficial for the medical and military sectors. Personal protective clothing with an integrated textile system and a wireless communication unit allows real-time monitoring of first responders, improving their efficiency and their own safety [1-3]. Typical, wearable textile antennas are patch antennas in which the antenna patch is made out of conductive material. In the case of a textile antenna, commercially available conductive coated textile materials, conductive yarns for embroidery or conductive inks can be used [1,4-10]. A non-conductive off-the-shelf fabric serves as the substrate for the textile antenna.

Many papers have been published on design, fabrication and application of textile antennas. A lot of research effort is put into obtaining antennas with smaller dimensions and with improved performance [11]. Hertleer *et al.* [2] proposed a truncated corner microstrip patch antenna on a flexible pad foam substrate; in another study by Hertleer *et al.* [6], a rectangular ring microstrip patch antenna was studied. Kennedy *et al.* [12] presented an eight-element microstrip patch antenna and Subramaniam and Gupta [13] developed a circular microstrip patch antenna, all made out of textile materials.

Hertleer [14] also applied the screen-printing technique, using silver-based ink on aramid fabric and concluded that screen-printing has powerful potential for manufacturing wearable antennas. However, the properties of these antennas were not tested after washing, which is inevitable when a garment with integrated antenna is being cleaned. Not many research groups are working on washability of textile-based antennas. Zhu and Langley [15] presented a textile antenna where the conductive material was a nylon fabric plated with copper and tin. They washed the antenna during a number of *hand washing cycles* and the performance of the antenna did not change. Nevertheless, since different textile materials have different properties, they suggested protecting the antennas with a waterproof layer. In the study by Scarpello *et al.* [16], the effect of using a thermoplastic polyurethane (TPU) coating on textile antenna performance was investigated. Furthermore, two different conductive materials, a copper-coated nylon fabric (electro-textile) and a conductive ink, were applied. Notwithstanding that both antennas were covered with a TPU coating, it was demonstrated that screen-printed antennas washed up to six times exhibit a more stable performance than those with an electro-textile. In the work by Kazani *et al.* [17] and Kim *et al.* [18], it was shown that the DC[1] conductivity of the screen-printed conductive textiles degrades significantly due to washing, demonstrating the necessity of coating. In the study by Kellomäki *et al.* [19], different coatings were compared as to their ability to protect the joint between an RFID (radio frequency identification) IC (integrated circuit) and a screen-printed textile antenna against laundering. In this design, some parts of the antenna remained uncoated. The frequency response of the RFID tag was measured after one washing cycle and only a visible inspection of the conductive ink after 10 washing cycles was performed and indicated a colour change of the ink.

In this paper, we extend the research into laundering screen-printed textile antennas up to 20 washing cycles. Furthermore, two different silver-based inks were used for printing the conductive layers and the performance of both uncoated antennas and coated antennas was investigated. This approach allowed us to investigate the necessity of coating, aiding the development of robust washable antennas. The performance of the screen-printed antennas was evaluated by measuring the reflection coefficient after each five washing cycles. Section 2 of the paper discusses the design of the wearable antenna, the choice of materials for the non-conductive substrate and the conductive inks used in this study. Section 3 describes the laundering of the antennas together with the measurement procedures executed for evaluating the wearable antenna performance. In Section 4, the results of this study are presented and discussed.

2. Wearable antenna design and fabrication

In order to assess the stability of the antenna's reflection coefficient after multiple washing cycles, a planar inset-fed textile antenna as depicted in Figure 1 is designed. The textile antenna used in this research consists of an electro-conductive patch, an electro-conductive ground plane and a non-conductive textile substrate. To measure the reflection coefficient, a SubMiniature Version A (SMA) connector is fixed with an electro-conductive silver-based glue to the microstrip feed line of the antenna.

A variety of textile materials have been used by different *Direct current* research groups as antenna substrate material: flannel of 100% cotton [1], polyester/cotton (65%/35%) [13], polyurethane foam and aramid fabric [20], felt [15], jeans cotton and polycot [21]. In this paper, two textile substrates were chosen: blended 20%/80% cotton/polyester (CO/PES) and 100% polyester (PES) woven fabric. These two materials were chosen because of their low moisture regain (MR) (Table 1). Hertleer *et al.* [14,22] recommend selecting textile substrate materials with an MR that is not higher than 3% to ensure stable antenna performance in varying environmental relative humidity conditions. The textiles used in this study have an MR of 0.2% and 2.5%, respectively (Table 1). The physical and

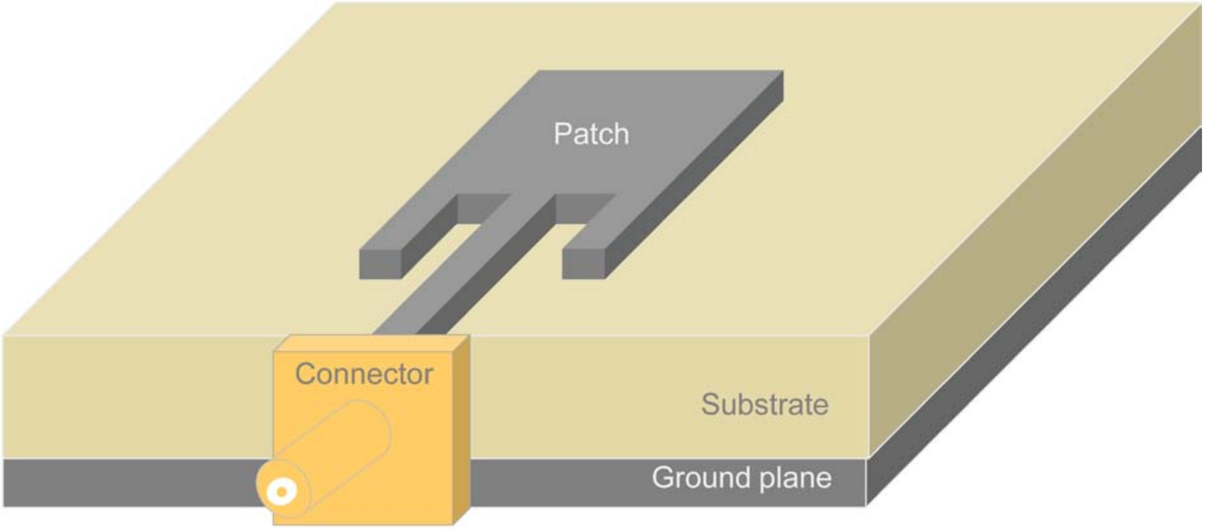

Figure 1. A microstrip inset-fed patch antenna.

Table 1. Properties of applied woven textiles as antenna substrate material

				Yarn density[5]		
Woven textile substrate	**Moisture regain[2] (%)**	**Thickness[3] (mm)**	**Basis weight[4] (g/m²)**	**Warp (threads/cm)**	**Weft (threads/ cm)**	**Type of textile weave[6]**
Cotton/polyester	2.5	0.702	252	39	18	Twill 4/1
Polyester	0.2	0.478	177	21	22	Plain 1/1

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[1] *Direct current*

mechanical properties (e.g. density, structure and thickness) of the textiles were determined according to ISO standards and are also listed in Table 1 (ISO/TR 6741-4:1987[2], ISO 5084[3], ISO 3801[4], ISO 7211-2[5], ISO 7211-1[6]).

In order to provide sufficient thickness to the antenna substrate, an assembly of multiple textile layers was used. For the substrate constructed from CO/PES, four layers of textiles were combined with an adhesive sheet that adheres when applying heat; for the PES substrate, six layers were combined.

Both the antenna patch on the top layer and the ground plane on the bottom were screen-printed (Figure 2) with conductive silver-based inks as this technique accurately produces any kind of pattern. Moreover, it is a fast and cost-effective method. The screen-printing was performed with a semiautomatic, Johannes Zimmer Klagenfurt - Mini MDF 482 printer. The ink is pushed through a patterned screen onto the fabric with a cylindrical squeegee with a 15 mm diameter. The mesh has a thickness of 115 µm and a sieve opening of 47%.

Two commercially available silver-based inks for screen-printing were used, DuPont (5025) ink from DuPont and Electrodag PF 410 ink from Acheson. According to the manufacturers, these inks are suitable to be applied on flexible substrates. The solid content, curing conditions, nominal sheet resistance and viscosity as indicated by the producers are given in Table 2.

For the two different substrates, two antennas operating in the range of the 2.45 GHz ISM[7] band were designed by means of Agilent's 3D planar EM field solver.

For an accurate design, substrate parameters such as substrate thickness (*h*), dielectric permittivity (*εr*) and loss tangent (*tanδ*) have to be known a priori. The thickness of the combined textile layers can be measured according to the ISO 5084 standard – *Textiles - Determination of thickness of textiles and textile products*. The permittivity (*εr*) determines the response of the

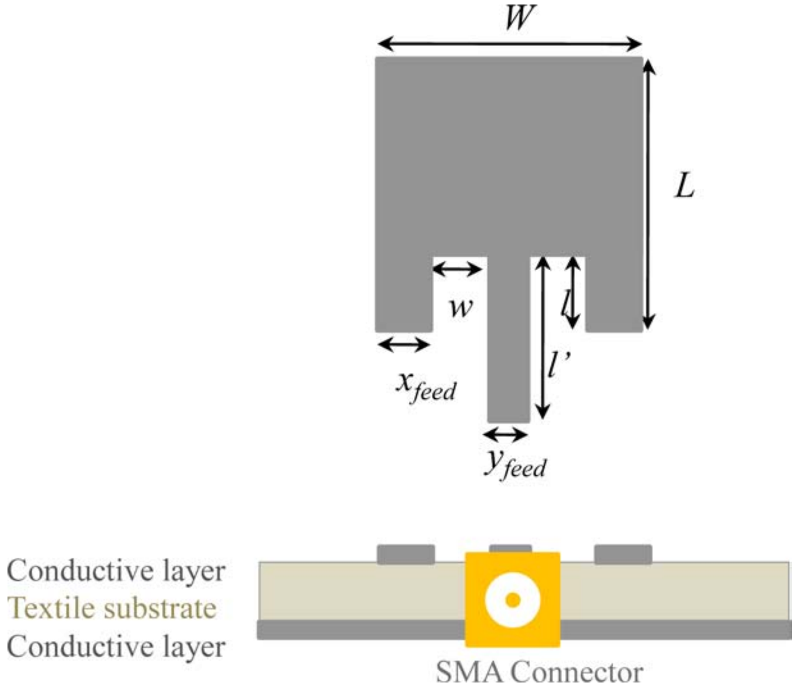

Figure 2. View from above and side-view of the microstrip inset-fed patch antenna

Table 2. Properties of the conductive silver-based inks

Ink type	DuPont ink	Electrodag ink
Solid content (%)	68–72	73.5–76
Curing conditions (120°C)	5–6 min	15 min
Sheet resistance (Ω/□ at 25 µm)	0.012–0.015	<0.025
Viscosity (Pa·s)	20–30	10–25
Resin	Epoxy	Polyester
Silver particle size (µm)	≤2.5	≤3

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[2] ISO/TR 6741-4:1987 "Textiles - Fibres and yarns - Determination of commercial mass of consignments - Part 4: Values used for the commercial allowances and the commercial moisture regains"

[3] ISO 5084 "Textiles - Determination of thickness of textiles and textile products"

[4] ISO 3801 "Textiles - Woven fabrics - Determination of mass per unit length and mass per unit area"

[5] ISO 7211-2 "Textiles - Woven fabrics - Construction - Methods of analysis - Part 2: Determination of number of threads per unit length"

[6] ISO 7211-1 "Textiles - Woven fabrics - Construction - Methods of analysis - Part 1: Methods for the presentation of a weave diagram and plans for drafting, denting and lifting"

[7] Industrial, Scientific, Medical band

material to an applied electrical field. The loss tangent (*tanδ*) characterises conduction losses inside the substrate. Both parameters can be determined as described in the work by Declercq *et al.* [23].

The dimensions of the two microstrip inset-fed patch antennas, one implemented on a CO/PES substrate and one constructed on a PES substrate, together with the properties of the substrate materials are given in Table 3.

In total, eight antenna prototypes were produced, four antennas used a CO/PES substrate and the other four antennas were printed on the PES substrate. From each group, two antennas used DuPont as conductive ink, whereas the other two used Electrodag as conductive ink for forming the antenna patch and the ground plane. In turn, from each group, one antenna using DuPont and one antenna using Electrodag as conductive ink were coated with a TPU layer from Epurex (thickness 80 μm), pressed on the antennas with a heat temperature of 160–170°C. The other two antennas of each group (again one with DuPont ink and one with Electrodag ink) remained uncoated. This coating protects the conductive planes during the washing process (Figure 3).

3. Laundering and testing of the antennas

In this study, the laundering behaviour of the printed textile antennas was performed in a reference washing machine according to the international standard ISO 6330:2000 – *Textiles - Domestic washing and drying procedures for textile testing* [24]. The washing programme 8A was chosen, as described in the datasheet of the manufacturer of the TPU layer. It washes at a temperature of 30±3°C, for a period of 3 minutes, followed by three rinsing cycles, two of 3 minutes and one of 2 minutes and concludes with a spinning time of 2 minutes. Reference detergents are added as requested by the standard and to reach a total load of 2 kg, ballast fabric is added to the antennas.

In our research, the printed antennas were subjected to a maximum of 20 washing cycles. After 5, 10, 15 and 20 washing cycles, the reflection coefficient and the antenna efficiency were measured to evaluate the intermediate effect. Each measurement required a completely dried antenna. In order to be sure that the antennas were entirely dry (as they were made up of four and six layers of textiles), they were put in a conditioned room with a temperature of 23±2°C and a humidity

Table 3. Dimensions and substrate characteristics of the microstrip inset-fed patch antennas.

Patch for CO/PES (mm)						**Substrate**	
W	42.5	*w*	6.25			*h (mm)*	2.808 (4 layers)
L	48.5	*l*	12.3	*l'*	*30*	*εr*	1.6
x_{feed}	10.5	y_{feed}	9			*tanδ*	0.02
Patch for PES (mm)						**Substrate**	
W	43,5	*w*	6.25			*h (mm)*	2.808 (6 layers)
L	50.3	*l*	12.3	*l'*	*30*	*εr*	1.5
x_{feed}	10.5	y_{feed}	10			*tanδ*	0.02

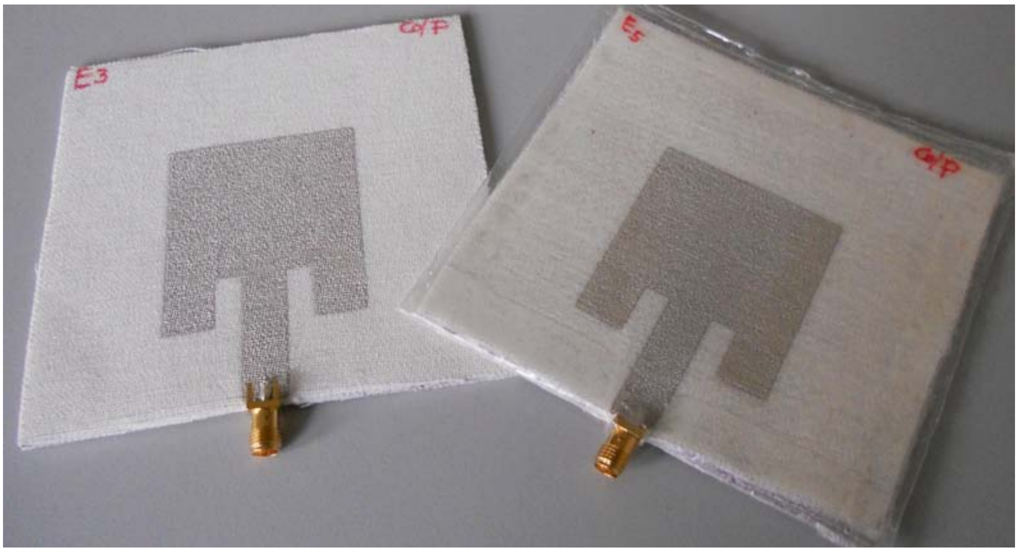

Figure 3. Printed antennas with conductive ink; left is an uncoated and right a coated antenna

of 50±4%, according to standard ISO 139 – *Textiles - Standard atmospheres for conditioning and testing* [24]. The antennas were weighed at intervals of 2 hours after reposing in that room for 24 hours. They were considered dry when two consecutive weighings showed a change in mass not greater than 0.25%. Following the drying process, the samples were put in a climatic cabinet for 24 hours at 20°C and at a relative humidity level of 65%. Next, a reflection coefficient measurement in the frequency range from 2 to 3 GHz, using an Agilent RF Network Analyzer, was performed.

4. Results

4.1 Cotton/polyester antennas printed with DuPont ink

The free-space reflection coefficients ($|S_{11}|$) before washing and after each 5th washing cycle, for up to 20 washing cycles of the uncoated and coated CO/PES-based antennas with Dupont ink, are given in Figures 4 and 5, respectively.

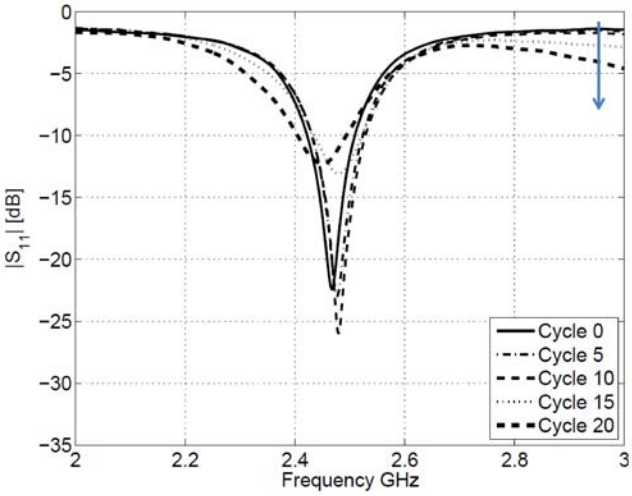

Figure 4. Free-space reflection coefficient before and after each 5th and up to 20 washing cycles of the **CO/PES** antennas with **DuPont** ink and ***without TPU layer.***

For the uncoated antenna in Figure 4, the reflection coefficient is relatively constant up to 10 washing cycles. However, after the 15th and 20th washing cycles, increased losses are observed since the resonance peak is slightly wider and the reflection coefficient at the highest frequencies (indicated with an arrow) decreases significantly. This can be attributed to degradation of the conductive glue used to attach the SMA connector to the feed line due to tumbling in the washing machine. In addition, on the printed surface, cracks were found after 20 washing cycles (see Figure 6 [22]).

For the coated antenna in Figure 5, the reflection coefficient remains relatively constant. From the 10th washing cycle, a widening of the resonance peak and a slight decrease of the reflection coefficient at the higher frequencies imply increased ohmic losses. In this case, the patch is protected by the TPU coating, hence, increased losses result from degradation in SMA connection quality and not from the conductive patch.

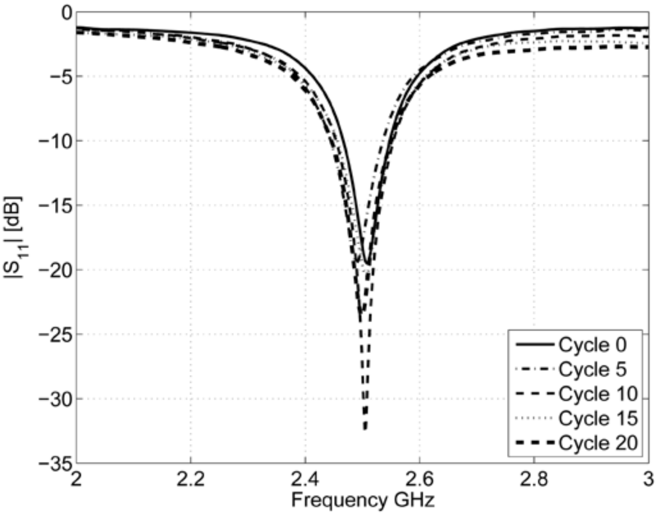

Figure 5. Free-space reflection coefficient before and after each 5th and up to 20 washing cycles of the **CO/PES** antennas with **DuPont** ink and ***with TPU layer.***

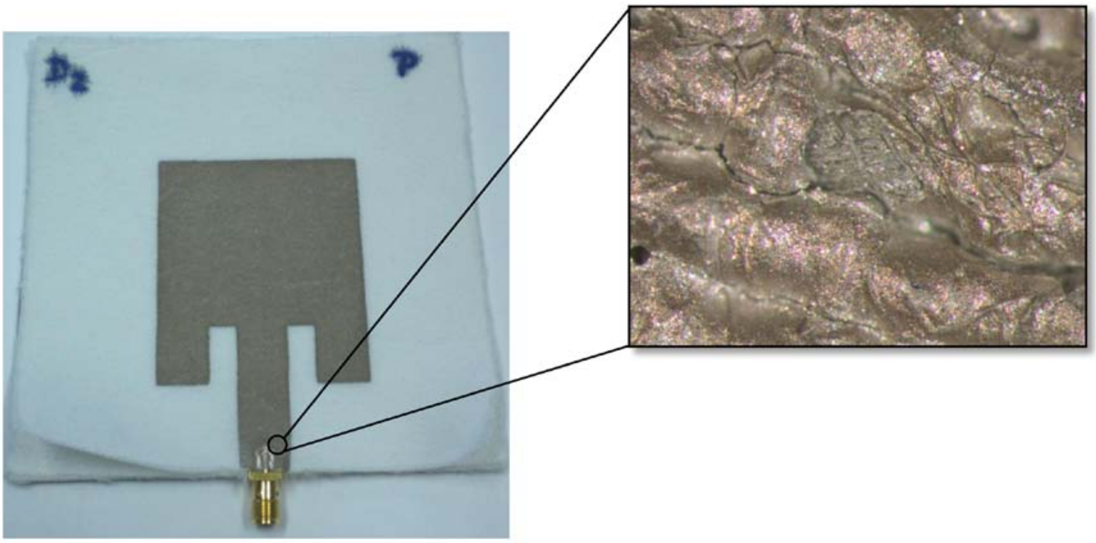

Figure 6. Cracks on the surface of the uncoated antenna of the screen-printed textile antennas washed 20 times (enlarged 63 times)

4.2 Cotton/polyester antennas printed with Electrodag ink

From Figure 7, we observe an increase in ohmic losses (broadening resonance peak, decrease $|S_{11}|$ at higher frequencies) after the 15th and 20th washing cycles. Nevertheless, these results show that even after 20 laundering cycles, the unprotected antenna presents acceptable antenna characteristics.

For the **coated cotton/polyester antenna** with Electrodag ink, the reflection coefficient behaviour as a function of increasing washing cycles, given in Figure 8, is relatively constant up to 10 washings. Hereafter, a large degradation in $|S_{11}|$ is observed. Since the antenna is coated, the abrupt change in antenna reflection coefficient behaviour results from connector detachment and not from a degradation of antenna patches and ground plane conductivity.

4.3 Polyester antennas printed with DuPont ink

For the **uncoated antenna** with DuPont ink, a delamination of the substrate was observed after washing, as shown in Figure 9. Hence, the substrate thickness increases, yielding a lower substrate permittivity because the substrate becomes less dense. This results in a resonance frequency shift towards higher frequencies and an increased bandwidth, as clearly observed from the $|S_{11}|$ measurements in Figure 10.

The reflection coefficient measurements of the **coated PES antenna** with DuPont ink, given in Figure 11, show a relatively constant behaviour up to 10 washing cycles. Hereafter, the reflection coefficient changes rapidly due to degradation of the SMA connector.

As shown in Figure 11, the coating process with TPU prevents delamination of the antennas made up of several textile layers.

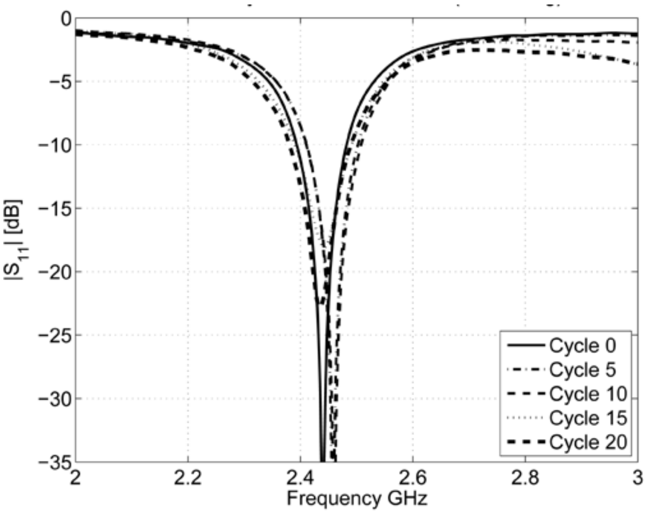

Figure 7. Free-space reflection coefficient before and after each 5th and up to 20 washing cycles of the **CO/PES** antennas with **Electrodag ink** and ***without TPU layer***

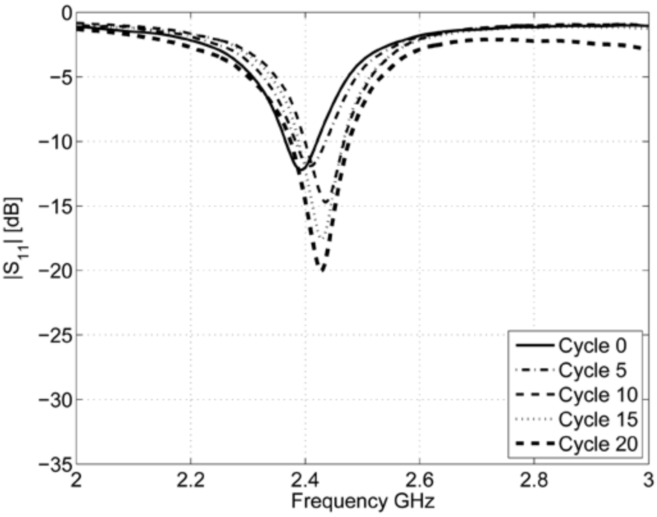

Figure 9. Free-space reflection coefficient before and after each 5th and up to 20 washing cycles of the **PES** antennas with **DuPont ink** and ***without TPU layer***

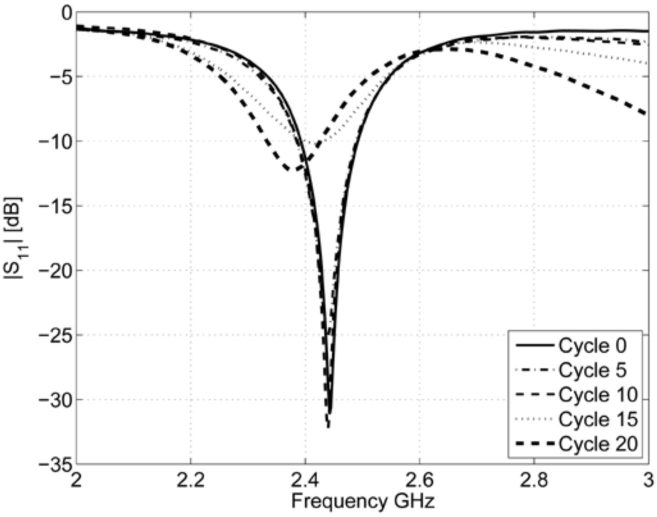

Figure 8. Free-space reflection coefficient before and after each 5th and up to 20 washing cycles of the **CO/PES** antennas with **Electrodag ink** and ***with TPU layer***

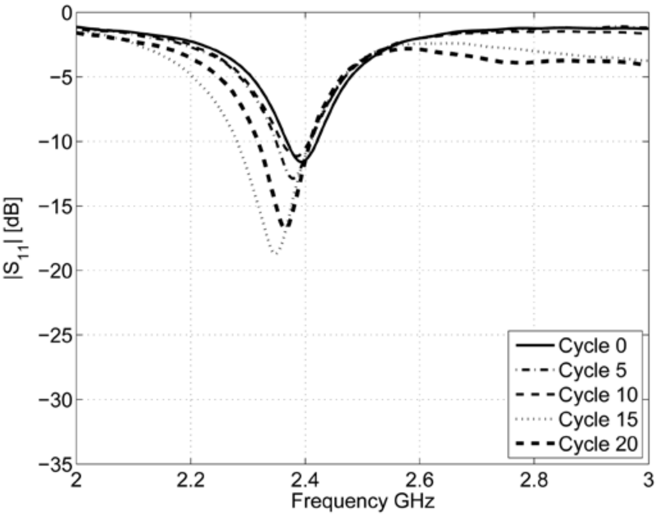

Figure 10. Free-space reflection coefficient before and after each 5th and up to 20 washing cycles of the **PES** antennas with **DuPont ink** and ***with TPU layer***

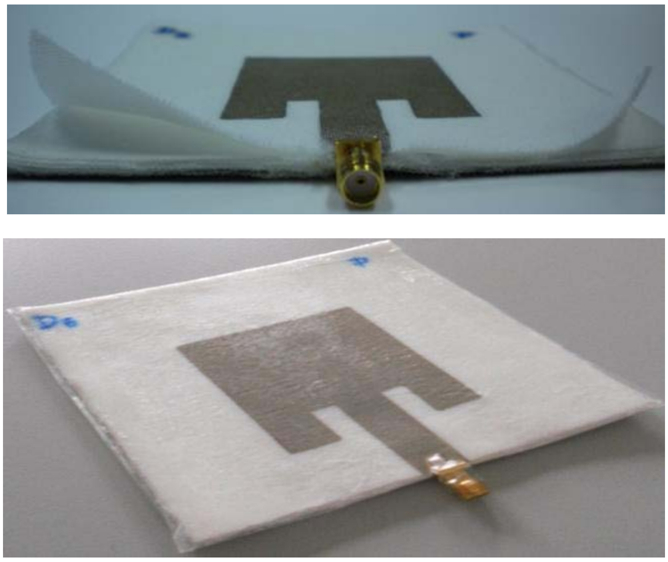

Figure 11. Delamination effect of the antenna caused by 20 washing cycles (up PES antenna *without TPU,* down PES antenna *with TPU*)

4.4 Polyester antennas printed with Electrodag ink

The free-space $|S_{11}|$ measurement depicted in Figure 12 of the **uncoated PES antenna** using Electrodag as conductive ink shows a relatively constant behaviour and this up to the 10th washing cycle. Also, the results of **the coated** counterpart, depicted in Figure 13, show a stable reflection coefficient as a function of an increasing number of washing cycles. Hence, we can conclude that the conductive ink is not degraded due to washing and that the SMA connections of these antennas did not detach.

5. Conclusions

In this paper, the influence of laundering on textile-based microstrip inset-fed patch antennas was studied. Antennas implemented on two different textile substrate materials, cotton/polyester and polyester, were taken into consideration. As conductive material to screen-print the antenna patch and the ground plane, two distinct conductive silver-based inks were used. The performance of the antennas, by measuring the reflection coefficient, was studied before and after coating with a protective thermoplastic (TPU) layer, and after 20 washing cycles. The antennas were protected with TPU because degradation of the conductive ink layer was expected after repeated washing cycles.

In conclusion, coating the antenna effectively protects the conductive ink from degradation and avoids delamination due to washing. The coating remains effective up to at least 20 washing cycles. However, some uncoated antennas still performed well after 20 washing cycles, which implies that the washing process does not significantly degrade the conductive ink. The main issue observed in this research was that after the 15th washing cycle, some connectors came loose or got even entirely detached from the antenna due to mechanical stress during the washing process. Moreover, this connection is required to measure the performance of the antenna.

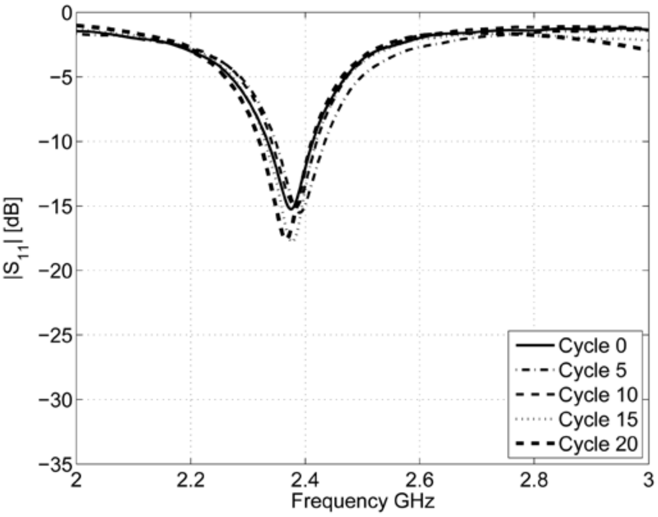

Figure 12. Free-space reflection coefficient before and after each 5th and up to 20 washing cycles of the **PES** antennas with **Electrodag** ink and ***without TPU layer***

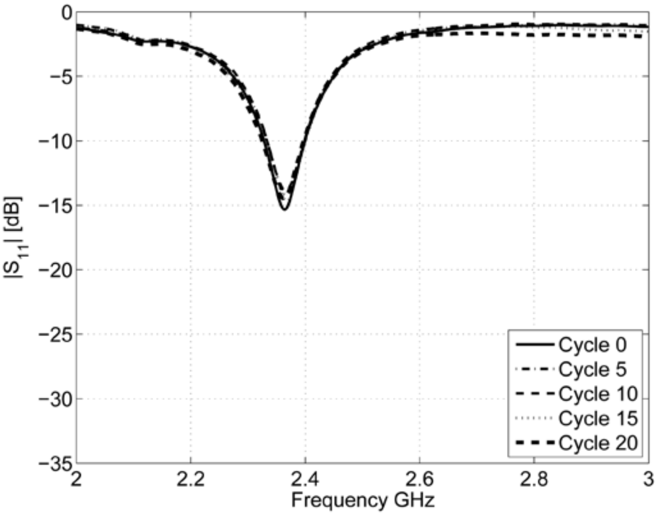

Figure 13. Free-space reflection coefficient before and after each 5th and up to 20 washing cycles of the **PES** antennas with **Electrodag** ink and with TPU layer

Nevertheless, coating with a protective layer prevents any degradation of the ink layer, but even more, avoids delamination of the multilayer antenna substrate.

In future work, a more durable and flexible electrical connection with the antenna needs to be established when performing washing tests.

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