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Effects of the fabric substrate on performance and durability of textile-embroidered dipole antennas

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Abstract

In this work, several fabrics with different composition and structure have been used as substrate for the production of wearable textile-embroidered dipole antennas. The performance of the antennas has been determined by measuring their resonance frequency, return loss and bandwidth. To determine their durability as wearable fabrics, the performance has been assessed before and after subjecting the antennas to washing and abrasion cycles. The results revealed that the woven fabrics presented a good washing fastness, even in fabrics having elastic fibers or low-crimp structures. In all cases, a good performance of the antennas was maintained after 30 washing cycles. For the abrasion cycles, the substrates with higher stability (measured as crimp ratio) presented a higher wear fastness, whereas a higher variability was observed for the substrates with lower stability.

Keywords:

Embroidered antennas, washing fastness, abrasion resistance, textile antennas, woven fabrics

1. Introduction

The rise of wearable products has driven to an increasing interest in smart garments owing to the possibilities that they can offer in safety, medical or leisure applications, among others (1,2). Smart garments often include integrated sensors and actuators that require the emission and reception of signals and data through a wireless connection, in order to offer novel functionalities to the wearer. Hence, antennas are a key component in wearables for their communication with the system. However, since most of these antennas operate under low-power wireless on-body applications with a short transmitter/receiver range —in the Wireless Body Area Network (WBAN)— they have to fulfil functional, safety and other comfort requirements. In this context, the integration of antennas into textile substrates is a good option to guarantee the comfort of the user, leading to reliable but unobtrusive systems for WBAN applications (3,4). Among all the possible techniques to manufacture textile-based wearable antennas —such as screen printing or conductive-foils attachment—, embroidery with conductive yarns is the most suitable integration technique in terms of design customization, presenting good repeatability and mass production availability (5).

The performance of textile-based wearable antennas depends on many factors such as their design (shape and dimensions) and the fabric's substrate properties, among others. Parameters such as the dielectric constant, thickness, moisture absorption or dimensional stability of the fabrics play a key role in the performance of the textile-based antennas (6). Moreover, textile-based antennas in smart garments should be washable and wearable (5), being the textile substrate selection a key aspect in the antenna development to ensure its performance and durability. Thus, the study of the effects of the textile substrates in the performance and durability of wearable antennas is of key relevance.

Although many studies have proven the feasibility of several kinds of textile antennas, fewer works in the literature evaluate the use of different textile substrates (6–14), and even less focus on textile substrates for embroidered antennas (5,15).

On the other hand, the durability of textile antennas obtained by conductive fabric layers (10,16–19), screen-printing (20,21) or embroidery (22–24) has been scarcely addressed, mainly focusing in washing fastness. In this sense, Zhu and Langley (10) successfully produced a dual-band coplanar patch antenna by using a conductive fabric over a felt substrate. The device was tested during and after hand washing cycles. They claimed that, although humidity caused a shift in the resonance frequency, the performance before and after washing in fully dried conditions remained unchanged, and suggested to waterproof the whole antenna to avoid changes due to washing. Fu et al. (16) produced dipole antennas for radiofrequency identification (RFID) tags from silver and copper conductive fabrics —also testing two different conformal coatings—, then submitting the tags to 10 washing cycles and measuring the antennas after each cycle. The authors found that the antennas with the textile glue coating could resist 10 washes maintaining a read range of 4-5 m. Corchia et al. (17) studied the durability of antennas produced with adhesive conductive nonwoven layers over a denim fabric. They subjected the antennas up to eight washing and ironing cycles, and concluded that their durability was closely connected to the quality and resistance to washing of the own adhesive. Simorangkir et al. (18) designed an ultrahigh-frequency radio frequency identification flexible antenna with a combination of a polydimethylsiloxane (PDMS) that percolated into the pores of a conductive fabric, achieving a good integration between both conductive and non-conductive parts. The antennas produced with this composite material where subjected to 15 washing cycles, and showed a minimum degradation in the read range. Also, Scarpello et al. (20) analyzed the washing fastness after 1, 3 and 6 washing cycles of screen-printed antennas on woven fabrics made of cotton/polyester before and after coating to protect the antenna. Using the coating layer, the antennas maintained an acceptable performance after 6 washing cycles. Kazani et al. (21) evaluated the washability of textile antennas produced by screen-printing on two polyester and cotton/polyester woven fabric substrates, with and without a thermoplastic polyurethane coating. The effectivity of the coating, especially on avoiding delamination, was proved after 20 washing cycles. Zhang et al. (22) reported a planar multiband antenna, obtained by embroidery, which the authors claimed to be robust to flexing and washing. Besides, Toivonen et al. (23) analyzed the impact of moisture and washing on the performance of embroidered antennas with conductive yarns in cotton fabrics evaluating the washing fastness after 2, 4, 6, 8, 10, 12 and 16 cycles. They found a reduction on the tag read range with washing. This fact was attributed to the dissolution of the conductive material and they suggested using a coating to protect the antenna. In a similar way, Tsolis et al. (5) suggested that the use of coatings on embroidered antennas can enhance their washability. For instance, Koski et al. (24) studied the washability of embroidered antennas under to 1, 2 and 3 washing cycles. They concluded that these antennas could withstand at least two washes, although also proposed an alternative technique, by immersing the tag in PDMS polymer. Their results showed that the PDMS polymer was not affected by washing, hence it could be used to protect the embroidered tags.

Nonetheless, wearable antennas can also suffer from deterioration due to wear. In the literature, a few works propose strategies to avoid abrasion —such as using textile covering layers to protect the antenna from harsh environments (25)—, or evaluate the effect of wear in the antennas performance. In (19), Xu et al. evaluated the effects of pilling, wrinkling, abrasion, and laundering tests on the resistivity of two conductive fabrics, and observed that pilling and abrasion caused a substantial damage to their resistivity. Then, they produced a textile antenna using these conductive textile layers and a denim textile substrate. Further abrasion and pilling tests lead to the same conclusion about the antennas performance, pointing out the importance of selecting the appropriate location of the antenna in order to avoid exposure to wear. However, to our knowledge, none of the works in the literature provides a complete study regarding both the washing and wear fastness while considering the structure and composition of the fabric substrates in which the antennas are embroidered. In this work, we present an evaluation of the effect of the textile substrate on the performance and durability to wash and wear of dipole antennas embroidered on several woven fabrics. For this purpose, firstly, the initial performance of the antennas under test is measured to evaluate the effect of the substrate. Afterwards, the performance of the specimens after washing cycles and after abrasion cycles is studied to evaluate their reliability and durability.

2. Materials and methods

2.1. Design and production of the textile antennas

2.1.1. Antenna's design

Half wavelength (λ/2) dipole antenna design was selected due to its small size, simple geometry, versatility and well-known good performance. The geometric parameters (see Figure 1) were defined to operate at a resonance frequency of 2.45 GHz —industrial scientific and medical radio band for WBAN applications—, following a previous work (15).

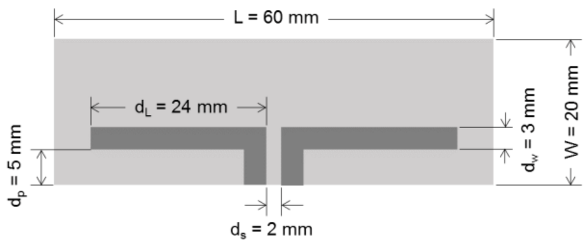


Figure 1. Design and dimensions of the textile antenna.

2.1.2. Textile substrates

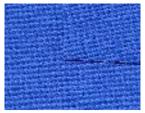
Six woven textile substrates were used: a jean-like elastic fabric made of cotton-polyester (JEANS), a satin cotton fabric (SATIN), an elastic cotton fabric (CO/EL), a heavy canvas-type cotton fabric (CANVAS), and two technical fabrics made from acrylic-cotton (PC/CO) and acrylic-cotton-polyamide

(RIPSTOP) mixtures. The main characteristics of these fabrics —composition, weave structure, areal weight, warp and weft yarn counts— are presented in Table 1.

The crimp is related to the waviness of the yarns in the fabric, which is caused by the own weaving process. The fabric crimp ratio can be an indicative of the fabric structure's stability, since the higher the amount of crimp inflections, the more difficulty for the yarns to slide. The fabric crimp ratio (K) was determined in both the warp and weft directions as the number of crimp inflections throughout the corresponding direction divided by the product of warp and weft yarns in the structure. For the sake of simplicity, the fabric crimp ratio given in Table 1 for each fabric is the average obtained from their K_{warp} and K_{weft} values.

Moreover, the thickness, moisture regain, dielectric constant and loss tangent of the fabrics were measured (see Table 1). The thickness was determined by means of a Mitutoyo precision palmer. A MOC63u Humidity Analyzer (Cobos Precisión, Spain) was used to measure the moisture regain of the fabrics. The permittivity measurements were conducted with a Split Post Dielectric Resonator and processed with the Microwave Q-Meter analysis software (QWED Company, Poland), from which the dielectric constant (ε_r) and loss tangent ($\tan \delta$) of the substrates were obtained.

Table 1. Main characteristics of the fabrics used as substrates.

Ref.	Back Face	**Composition**	**Weave structure**	**Areal weight** [g/m²]	**Yarn count** (warp / weft) [yarns/cm]	**Fabric crimp ratio** (K)	**Thickness** [mm]	**Moisture regain** [%]	**Dielectric constant** (ε_r)	**Dielectric loss tangent** (tan δ)
JEANS		70%*Cotton (CO) 29* Polyester (PES) 1%* Elastane (EL)	Twill	290	54 / 17	0.56	0.60	3.8 ±0.4	1.562 ± 0.009	0.034
SATIN		100% Cotton (CO)	Satin	225	38 / 21	0.25	0.49	3.8 ± 0.1	1.585 ±0.003	0.041
CO/EL		99%* Cotton (CO) 1%* Elastane (EL)	Twill	260	40 / 20	0.67	0.50	4.5 ±0.2	1.659 ±0.007	0.052
CANVAS		100% Cotton (CO)	Plain	315	43 / 26	1	0.61	3.3 ±0.2	1.606 ±0.007	0.028
PAN/CO		54% Acrylic (PAN) 44% Cotton (CO) 2% Antistatic fibres	Twill	280	26 / 26	0.67	0.38	1.8 ±0.2	1.904 ±0.008	0.034
RIPSTOP		50% Acrylic (PAN) 41% Cotton (CO) 7% Polyamide (PA) 2% Antistatic fibres	Plain (ripstop)	330	35 / 22	0.85	0.48	2.7 ±0.1	1.840 ±0.009	0.034

Note: Values marked with (*) are estimated.

2.1.3. Antennas embroidery

Textile antennas were embroidered with a Singer Futura XL-550 Embroidery Machine (*Singer Corporation*, USA). A fixed contour fill (15) pattern (i.e. geometric parameters and stitch characteristics) was used for all the substrates. The embroidery technique requires two threads. As top thread —which remains at the face side— a 100% polyester yarn was used. As bobbin thread —which remains in the reverse side—, a Shieldex® conductive two-ply twisted yarn of 140 dtex (*Statex Produktions & Vertriebs*, Germany) with a linear resistance of less than 30 Ω/cm was used. Since this is a silver-coated polyamide 66 thread, it was used as bobbin thread to reduce the wear of the conductive coating during the embroidery process. Ten specimens per sample were prepared: 5 for washing fastness evaluation, and 5 for wear fastness evaluation.

2.2. Evaluation of the performance and durability

2.2.1. Antennas' performance evaluation

The antennas' performance was evaluated according to their return loss (S_{11}), resonance frequency (f_r) and bandwidth (BW) at S_{11} = -10 dB, which were measured by means of a FieldFox Microwave Analyzer (*Keysight Technologies*, USA) operating on vector network analyzer mode. SMA 50Ω end launch connectors (*Johnson-Cinch Connectivity*, USA) were attached at the differential input of the textile dipoles under test to perform the measurements. Specimens were conditioned for 24 h prior to each measure. The initial performance of each sample was determined as the average of all the 10 specimens prepared in unwashed and non-wear conditions.

2.2.2. Washing fastness and wear fastness tests

The durability of the antennas was studied in terms of resistance to washes (washing fastness) and abrasion resistance (wear fastness).

To evaluate the washing fastness, the embroidered antennas were subjected to washing cycles in a Balay Laboratory Washing Machine (*BSH Electrodomésticos España*, Spain) using a typical domestic washing program —1h 30 min, 40 ºC, 1000-rpm spin-dry—. An ECE-color standard detergent was added in a concentration of 1% w/w. A 10-min drying cycle performed at 60 ºC on an air oven was performed after each washing cycle. The performance of each of the 5 specimens per sample was characterized initially (0W) and after 5, 10, 20 and 30 washing cycles (5W, 10W, 20W and 30W, respectively) as described below.

Moreover, the dimensional stability with washings (shrinkage) was evaluated measuring the gap between dipoles (d_S) and the total length between dipoles' ends (d_L+d_S+d_L) of each specimen by means of an ImageJ software from scans of the antennas at a 2400 dpi resolution for a better accuracy. The results were statistically treated by means on an analysis of variance (ANOVA) and a Tukey HSD test.

To evaluate the wear fastness, abrasion tests were performed in a 4769 Multi-motion Pilling Tester (*United States Testing CO*, USA). Five unwashed specimens per sample were analyzed. Each specimen was secured in an eccentric rotating disc, leaving the conductive yarn of the antenna exposed to the action of a hard brush for the specified number of cycles. Each specimen's performance was characterized initially (0A) and after 25, 35, 45 and 55 abrasion cycles (25A, 35A, 45A and 55A, respectively).

3. Results and discussion

3.1. Textile substrates characterization

The dielectric constant and loss tangent, thickness, moisture regain and fabric crimp ratio —as indicative of the structure's stability— of the textile substrates under study were determined to try to elucidate the effect of the textile structure on the performance and durability of the antennas. The results are presented in Table 1.

According to the literature (6), the performance of antennas mainly depends on the permittivity (i.e., the dielectric constant ε_r), thickness of the substrate, moisture content and the mechanical deformations. ε_r, one of the most relevant parameters, is highly influenced by many factors such as the composition and structure of the fabric or the moisture content, among others (6). Typically, textile substrates with low ε_r are preferred to minimize surface waves and to improve the bandwidth, although this leads to an antenna of higher dimensions, hence this requires reaching a trade-off.

The permittivity (ε_r) of the textile substrates used in this study was similar and presented a low variability, with values varying between 1.56 and 1.91, hence being controlled in a stable range. These values are also in well agreement with those found in the literature (5,11,26). On the other hand, the loss tangent (tan δ) values were found in the range between 0.028 and 0.052, which are also consistent with previous work (5) and they guarantee a moderate level of losses. This fact allows designing wearable antennas for WBAN with good performance.

The thickness of the samples was in the range between 0.37 and 0.61 mm.

Concerning to the effect of the moisture, the presence of water molecules in the fabric substrates can highly affect their dielectric properties increasing both the relative permittivity and loss tangent (8). As shown in Table 1, samples containing mainly cotton presented moisture regain values ranging from 3.3% to 4.5%, whereas the fabrics with mixture of cotton and acrylic fibers revealed lower percentages around 1.8-2.7%. Although higher ε_r and tan δ were expected in samples with higher moisture content (6,27), the different samples in this study did not reveal a clear relationship between these parameters. This fact can be attributed to the differences in the structure and composition of each fabric, meaning that such an effect —previously observed in the literature (8)— is mainly observable when comparing moisture variations within the same substrate.

As aforementioned, the fabrics' crimp ratio (K) was determined to evaluate the structural stability of the substrates. Although K was lower for the SATIN than the JEANS, the presence of elastic fibers in the weft direction makes the latter be more stretchable than the former, leading to a higher deformability of the JEANS substrate. Similarly, for the CO/EL substrate, although having an elastic fiber in the weft direction, its high K provides a good stability for the antenna.

3.2. Evaluation of the antenna performance

3.2.1. Substrate's effect on the initial antenna performance

The determination of the initial performance of each sample led to evaluate which is the influence of the fabric substrate in the resulting antenna. The average values of resonance frequency (f_r), return loss (S_{11}) and bandwidth (BW) defined at S_{11}= -10 dB for all ten initial specimens are summarized in Table 2.

Table 2. Average values for the initial antenna performance.

Ref.	**Average resonance frequency (f_r),** [GHz]	**Shift vs f_o** [%]	**Average return loss** (S_{11}), [dB]	**Average bandwidth** (BW), [MHz]
JEANS	2.41 ±0.37	-1.8%	-25.2 ±5.1	647 ±188
SATIN	2.63 ±0.08	7.4%	-28.8 ±4.2	716 ±114
CO/EL	2.45 ±0.13	0.2%	-27.1 ±10.1	693 ±185
CANVAS	2.36 ±0.08	-3.5%	-20.6 ±7.3	639 ±262
PAN/CO	2.24 ±0.09	-8.5%	-20.9 ±3.8	542 ±117
RIPSTOP	2.33 ±0.07	-5.0%	-21.9 ±7.9	700 ±71

Note: f_o = 2.45 GHz

In general, good results were observed in the samples, considering the general behavior of textile substrates. The dipoles resonated at frequencies between 2.24 GHz and 2.63 GHz, near the operation frequency (f_o) designed to be 2.45 GHz. This supposes a shift vs the f_o up to 8.5%, that is considered reasonable by taking into account the tolerances of the embroidery manufacturing process, as well as the measurement uncertainties. Regarding the initial return loss, all the samples presented excellent average values, ranging from -20.6 dB to -28.8 dB, being the SATIN substrate the one with a better initial performance giving an average return loss of -28.8 dB (note that the minimum threshold level for the required S_{11} is -10 dB). In all cases, the average f_r and S_{11} values determined are in good agreement with the results obtained in previous studies (15).

On the other hand, the average bandwidth of the antennas was between 542 MHz and 716 MHz. These values are near double than the expected BW=337 MHz —obtained from simulations for a dipole antenna embroidered on a 100% cotton fabric (15)—, meaning that the bandwidth allows operation for wider band applications. These differences can be attributed to the measurement tolerance, as well as to other effects such as the impact of humidity and temperature on the effective dielectric permittivity, the tolerance of the embroidery manufacturing process, or the own roughness of the textile substrates (i.e. non-uniform thickness of specimens) (15).

Nonetheless, in general terms, the measurements revealed a good accordance with the design specifications regardless the fabric used as substrate. From these results, it can be concluded that the different substrates used in this study lead to similar performance of the embroidered antennas.

3.2.2. Washing fastness

For evaluating the durability to washing cycles, the antennas were subjected to 5, 10, 20 and 30 washing cycles. The evolution of resonance frequency (f_r), bandwidth (BW) and return loss (S_{11}) with washings is plotted in Figure 2. In addition, the dimensional stability of the antennas and the dielectric properties of the fabrics were evaluated also at those points, in order to understand their effect on the antennas' performance.

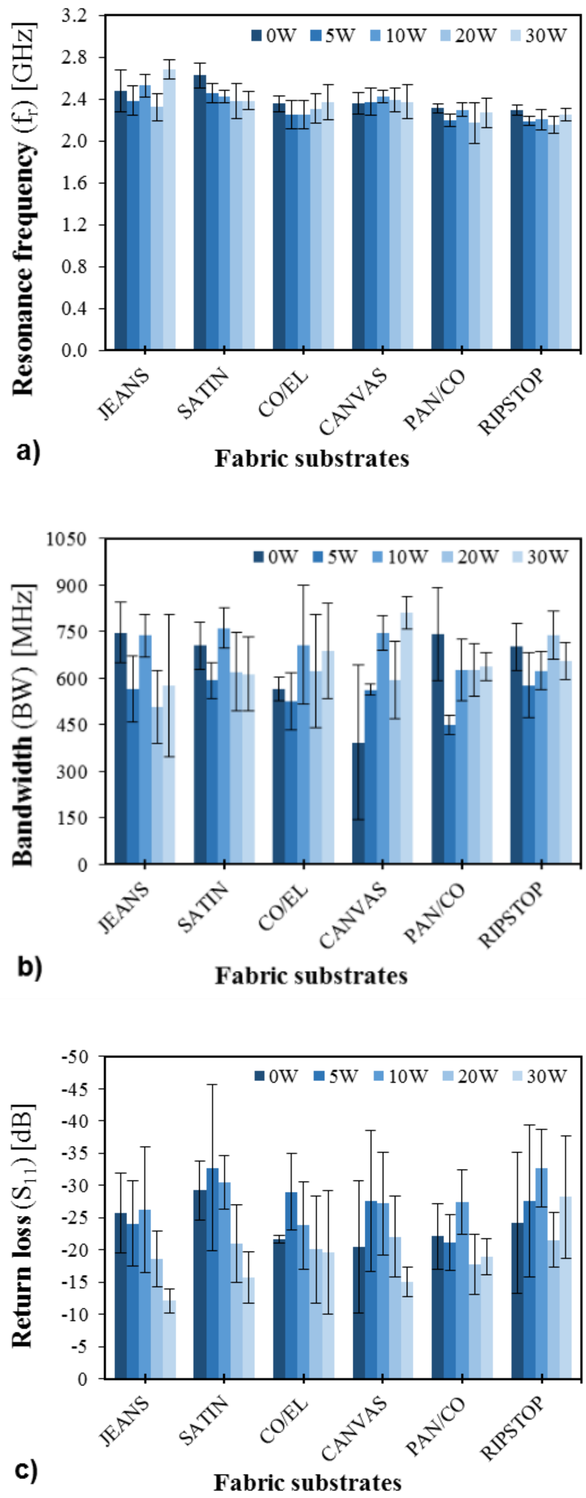


Figure 2. Evolution of the resonance frequency (a), bandwidth (b) and return loss (c) with the washing cycles.

Concerning to the durability to washing, after 30 washing cycles the antennas maintained their resonance frequencies (Figure 2a) around ±9% of the initial (0W) f_r values for the JEANS and SATIN samples, and around ±6% respect the initial f_r values for the CO/EL, CANVAS, PAN/CO and RIPSTOP samples. This is consistent with the small variations in ε_r with washings and with the good dimensional stability of the antennas (examples shown in Figure 3) where only slight differences were observed. In fact, a difference between of the total length (d_L+d_S+d_L) of the unwashed specimens with respect to the washed ones was determined, revealing a limited contraction in the overall length between a 1.8% and a 3.8%. This means that the significant variation of the distance between dipole ends of the antennas was produced during the first 5 washing cycles. Nonetheless, since the total length of the antenna was only reduced around 3%, the resonance frequency remained approximately stable, thus pointing to their reliability. Besides, the differences for the gaps between dipoles (d_S) were non-significant in all cases. Therefore, the geometry and the embroidery maintained the central part of the pattern and suffered only a limited shrinkage, helping to maintain the antennas' performance.

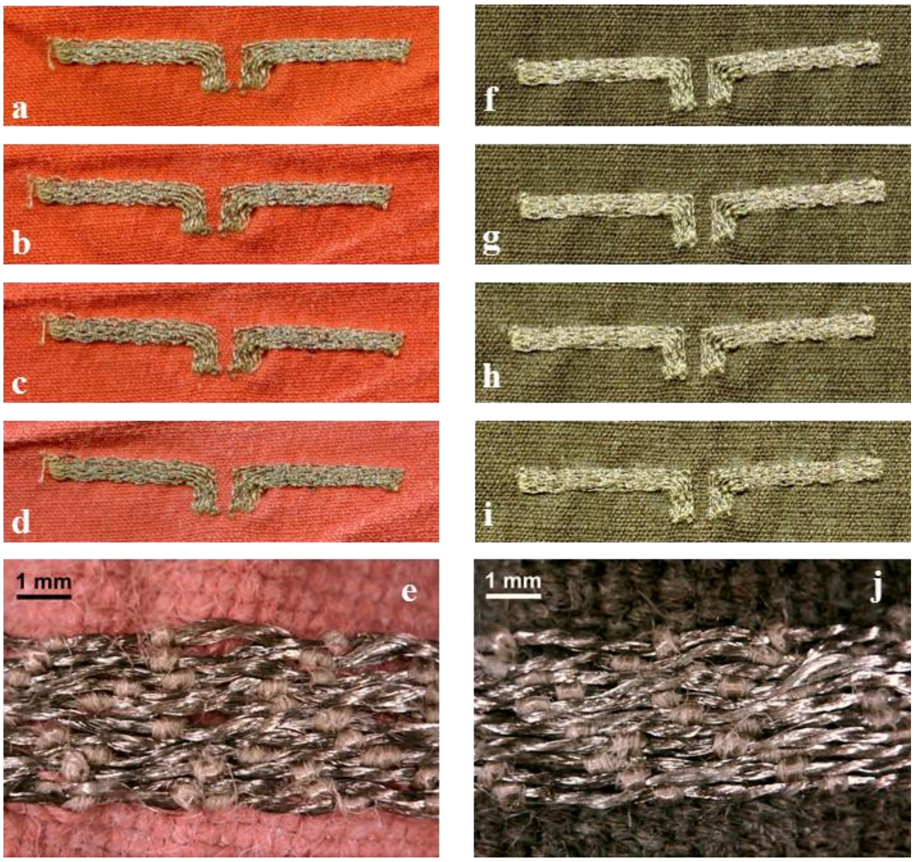


Figure 3. Evolution of one antenna embroidered in the CO/EL (left) and RIPSTOP (right) substrates after 5 (a, f), 10 (b, g), 20 (c, h) and 30 (d, i) washing cycles. Bottom images show a magnification of the embroidered antenna in the CO/EL (e) and the RIPSTOP (j) substrates after 30 washing cycles.

Regarding the ε_r and considering that these measurements are highly sensitive to the aforementioned parameters of humidity, temperature, substrate roughness, etc., the results seem to remain stable in general terms, with variations lower than 10% with respect to the unwashed conditions in most of the cases. However, as shown in Figure 4, a certain trend towards a slight increase of the substrates' dielectric permittivity with washings can be observed. This could be attributed to variations in the compactness of the fabrics and the yarns' capillarity, which would increase their affinity for water, hence increasing their dielectric permittivity.

However, according to the results obtained, the variation of the substrate with washings presents only a very small effect on the evolution of the antennas' performance, hence it can be considered negligible.

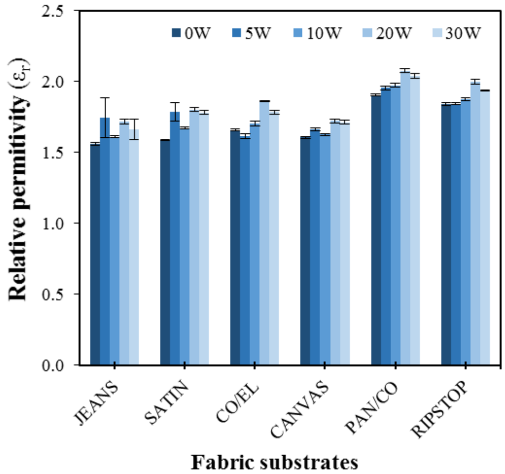


Figure 4. Evolution of the dielectric constant (ε_r) with washings.

As shown in Figure 5 for two characteristic specimens, an enhancement of the BW as well as a reduction of S_{11} at resonance frequency is observed with washings. This fact is expected, since the number of cycle washings remove some metallic particles from the yarn and, thus, the antenna losses are increased.

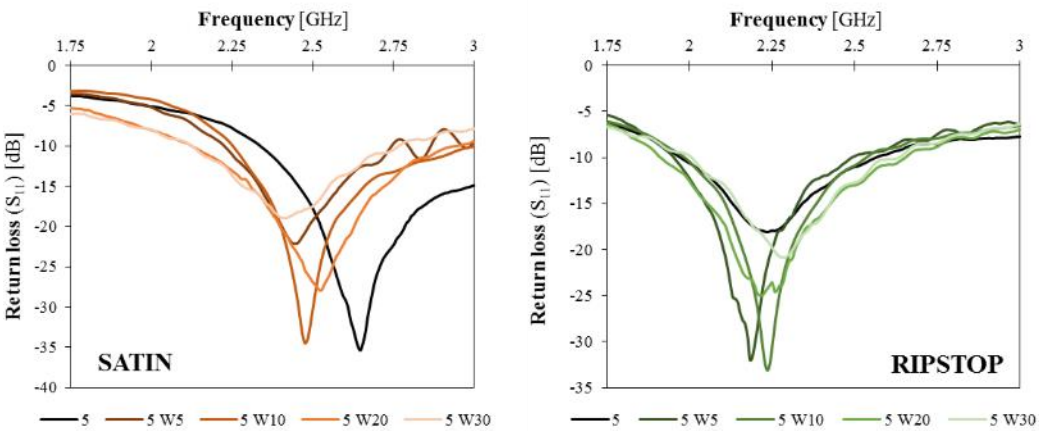


Figure 5. Return loss curves for characteristic specimens of SATIN sample (left) and RIPSTOP sample (right).

3.2.3. *Wear fastness*

Concerning to the wear tests, it was observed that the embroidered antennas did not show relevant physical damage due to abrasion even after 55 cycles, as can be observed in Figure 6. It can be seen in Figure 6e and 6j that some fibers corresponding to the polyester top yarn arise from the surface, while the conductive multifilament yarn that draws the antenna pattern is almost unaffected. Although the evaluation of the antennas' performance showed despair results depending on the type of substrate, all the antennas presented good performance after the abrasions tests (Figure 7).

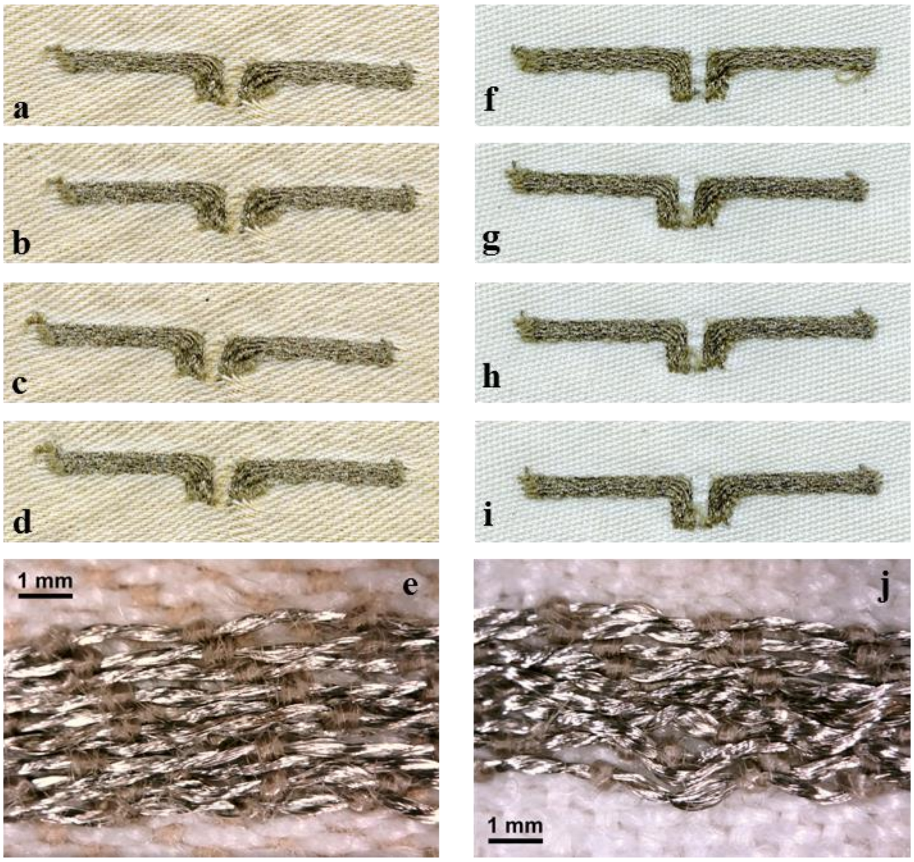


Figure 6. Evolution of one antenna embroidered in the SATIN (left) and CANVAS (right) substrates after 25 (a, f), 35 (b, g), 45 (c, h) and 55 (d, i) abrasion cycles. Bottom images show a magnification of the embroidered antenna in the SATIN (e) and the CANVAS (j) substrates after 55 abrasion cycles.

Regarding f_r (Figure 7a) CANVAS, PAN/CO and RIPSTOP series showed similar values with reduced standard deviation (SD) even after 55 cycles, where the shifts with respect the original conditions were up to 7%, similarly to those obtained for the washing fastness. CO/EL, SATIN and JEANS series revealed a lower regularity with higher SD. However, all the samples antennas could maintain their f_r, even after 55 wear cycles, with a shift below 6% in most cases and below 15% in all of them, which is a very significant result.

The return loss results (Figure 7c) presented again a higher SD for the JEANS, SATIN and CO/EL series, but in general, no clear trends could be observed for the variation of the antennas performance with the abrasion cycles. In fact, the S_{11} was in all cases lower to -10 dB, hence all of the samples fulfilled the return loss performance again.

Concerning to the BW, all the samples presented high variability on the BW results, with high SD — although these were slightly higher for the JEANS series—, this hindering possible trends in the effect of the wear on the bandwidth performance of the antennas.

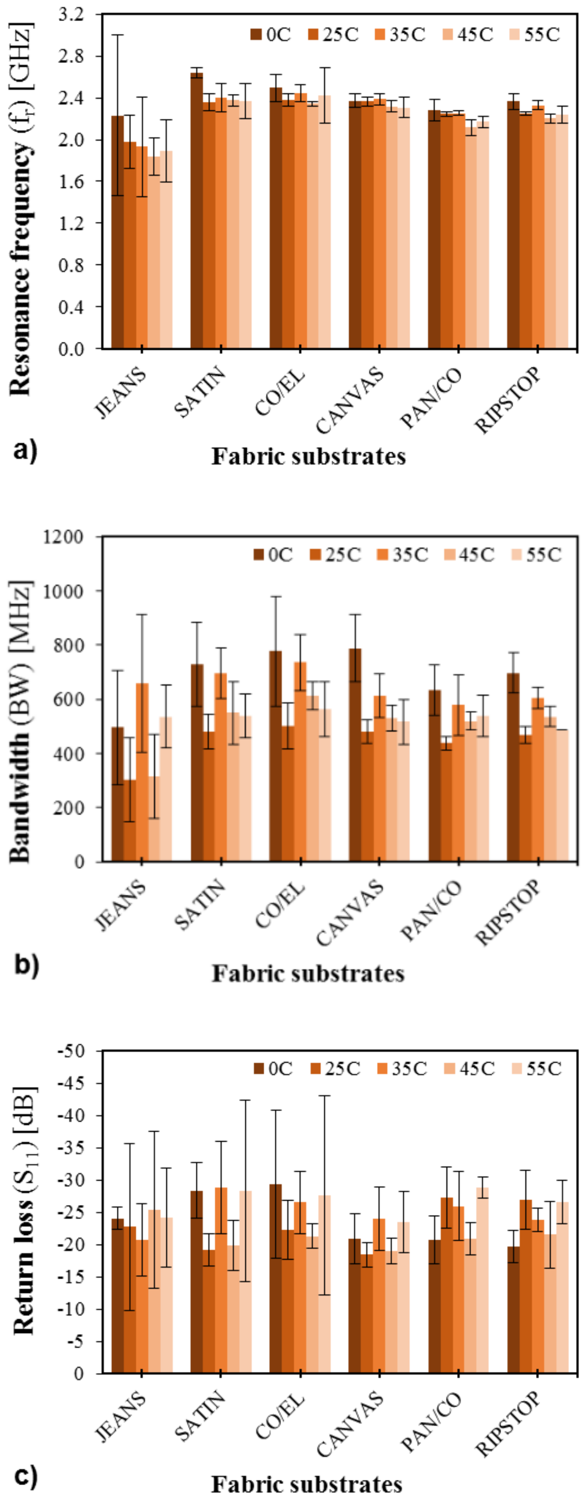


Figure 7. Evolution of the resonance frequency (a), bandwidth (b) and return loss (c) with the abrasion cycles.

Regarding the variability on the measurements, it has to be taken into account that both the fabrication process tolerance and the sensitivity of the measurement processes are common difficulties in antenna design, especially when working with non-rigid substrates such as textile antennas. However, the three samples presenting higher variability in their performances (JEANS, SATIN and CO/EL), also present a lower dimensional stability of the substrates —owing to their content of elastic fibers and/or their lower crimp coefficients—. According to the results, fabrics with elastic fibers (CO/EL) or low structural stability (SATIN) can also perform as excellent substrates for embroidered antennas. Fabrics combining both —hence having elastic fibers and low-crimp weave structures, such as the JEANS substrate— can also be used, although a higher variability in their performance due to abrasion must be expected. In this sense, the efficiency of using backing fabrics for increased stability should be assessed in further studies, as well as the variation of their performance during stretching.

4. Conclusions

As a general conclusion, it has been found that all the fabrics studied are feasible to be used as substrates for antenna embroidery. Even fabrics with low dimensional stability —such as fabrics with low-crimp structures or containing elastic fibers— did not have such a great impact on the antenna performance. However, the fastness of the antenna seems to be affected, especially the wear fastness, when both elastic fibers and low-crimp structures are combined. To evaluating such an effect, a further comprehensive study with a wider range of elastic woven fabrics should be addressed.

Although significant differences in the total antennas' length were observed to take place between the original state and after the first 5 washing cycles, these differences had a reduced impact in their overall performance. The antennas' performance presented in this study show a good washing fastness for all substrates after 30 washing cycles, and a good wear fastness of all substrates after 55 cycles, since the shifts in the resonance frequencies were kept low while fulfilling the return loss performance (S_{11} < -10 dB) in all cases.

Once optimized the antenna's design, antennas embroidered on woven fabrics with structures and materials similar to those assessed in this study should present a good performance even after 30 washing cycles or although suffering abrasion due to wear. However, some care has to be taken when using woven fabrics containing elastic fibers if low-crimp weave structures are chosen.

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