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Effect of Textile Pretreatment Processes on the Signal Transferring Capability of Textile Transmission Lines

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Abstract
Transmission lines in the textile structure are a path of supplying power or transmitting digital/analog signals to electronic components in a textronic system. The current experimental investigation concerned potential differences in the signal transferring capability of textile transmission lines that were subjected to different pretreatment processes. In this study, 11 conductive yarns (stainless steel, silver plated PA and insulated copper) with different linear resistance values were used to create transmission lines through different weave patterns. E-fabric structures containing transmission lines were subjected to combined desizing, alkaline scouring and hydrogen peroxide bleaching pretreatment processes. Signal-to-noise measurements were performed before and after each pretreatment process. In order to make any reasonable comparison of the signal transferring capability of e-fabric samples, recorded signals were analysed using Matlab ® and their SNR values were also compared statistically. The results show that the pretreatment processes, the linear resistance of conductive yarns and the type of weave structure significantly influence the signal transferring capability of the transmission lines.

Key words: *transmission lines, signal transferring, pretreatment, conductive yarn, e-textiles, smart textiles, bleaching.*

Introduction

the new field of science dealing with the implementation of electronics to textiles in combination with informatics is known as textronics. A complete textronic system would consist of a sensor, actuator, data processing unit, and energy storage device with interconnections. In a textronic system, to achieve reliable electrical transmission among electronic components without any interruption is an extremely important issue since such interconnections are a path of supplying power or transmitting digital/analog signals to electronic components [1, 2].

Recently great effort has been made in order to obtain reliable and stable textile transmission lines. Apart from the electrical properties of transmission lines, research is still trying to comprise desirable aspects of clothing comfort as well. There are many possibilities to obtain textile transmission lines with different levels of electrical conductivity. Indeed the conductivity level over the textile substrate depends on the kind of application e.g. electromagnetic interference (EMI) shielding, static control, smart clothing prototypes etc. [3]. Textile transmission lines for different applications have been obtained through several methods such as direct insertion of conductive yarns during weaving or knitting processes, the deposition of electroconductive thin layers on a flat textile surface, the overprinting or coating of conductive materials/polymers like polypyrole, polyaniline, polytiophene, etc, as well as metal particles, carbon nanotubes and carbon black particles on a flat textile surface and direct insertion of conductive yarns through sewing or embroidery methods [4 - 7]. In all methods the key issue is how much conductivity is required and desired over the transmission line considering comfort aspects as well. However, obtaining a transmission line for prolonged use is not an easy task, because during usage, transmission lines are subjected to numerous mechanical stresses, moisture and perspiration impacts etc., which can lead to the failure of the line in terms of resistivity and signal transmission. The value of this failure can either decrease the quality of signal transmission or further result in the failure of the whole textronic system.

Apart from usage issues after production, the failure of textile transmission lines can also occur during the construction stages. For instance, during the insertion of conductive yarns in the weaving/ knitting processes, or through the embroidery or sewing methods conductive yarns are also subjected to mechanical stresses that result in loss of conductivity. In the method of printing or coating, the density level of conductive materials in the form of ink or parameters affecting the printing/coating processes such as temperature, duration etc. can also influence the conductivity level of layers deposited on the textile substrate. Such kinds of problems encountered during the construction stages or during the usage of transmission lines have caught the interest of researchers. For instance, the influence of washing on the electric charge of the coated conductive yarns [3, 8, 9], the impact of ambient parameters on the electrical properties of transmission lines [2], and the electrical resistance of textile transmission lines under wet conditions [10] were recently discussed.

However, before constructing transmission lines it may also be important to know the impact of textile pre-production stages on the electrical resistance and signal transferring capability of transmission lines, and so far in the literature no attention has been paid to this issue. From a textile view point, it is well known that woven or knitted fabrics made of native cellulose fibres include different kinds of impurities that have to be removed through a number of processes prior to dyeing [11]. In order to remove these impurities, the scouring of cotton fabric is one of the important steps, which is normally carried out with strong alkali at high temperature and for longer duration [12, 13]. In addition to scouring, bleaching is carried out in order to remove any unwanted colour from the fibres. This process also helps to eliminate any traces of other impurities remaining from the previous preparation steps and improves the absorbency of the textile material for dyeing and printing [14], and so on. However, although the chemicals used in pretreatment and finishing processes remove the impurities, they also attack the fibre structure, leading to a reduction in strength [11]. Thus

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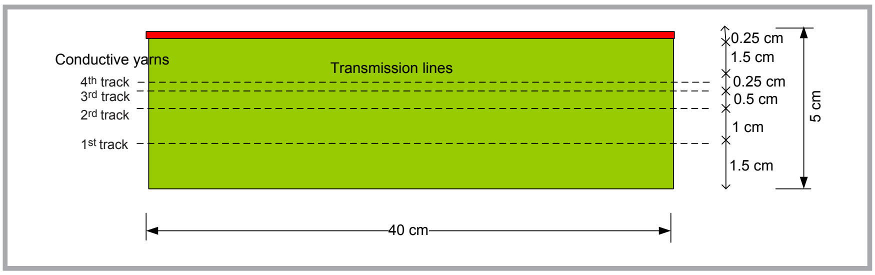

Figure 1. *Diagram for the design of transmission lines in a woven fabric.*

Table 1. *Characteristics of conductive yarns used as transmission lines.*

Conductive yarn no.	Material type	Weight, g/m	Linear resistance, Ω/m
1	Insulated copper	0.144	<5
2	100% stainless steel	1.9	<5
3		0.54	<15
4		0.28	<25
5		0.19	<45
6		0.11	<60
7	Silver plated nylon	0.125	<50
8		0.0625	<80
9		0.0113	<420
10		0.00441	<1600
11		0.00450	<2000

if a fabric containing conductive yarns used as transmission lines is produced by the weaving or knitting process and then subjected to pretreatment finishing processes, it can be affected by the chemicals or finishing parameters as chemicals, and the high temperature/duration may cause a loss of conductivity and decrease in the signal quality of the transmission line as well. Considering this important issue, in this research the effect of textile pretreatment processes on the signal transferring capability of textile transmission lines was discussed using both signal and statistical analyses. According to a literature survey, since mainly silver coated [15 - 17], stainless steel [18 - 23] and copper coated yarns [22, 24 - 26] are preferred to construct transmission lines, in our study combinations of those yarns with different linear resistance values were also used.

The following section describes the construction of textile transmission lines using 11 different conductive yarns at different distance intervals, followed by pretreatment finishing processes: desizing, scouring and bleaching, measurement of the signal transferring capability and determination of the signal- to- noise ratio (SNR) with signal analysis explanation. The last section reports the results obtained from measurements before and after each pretreatment process, with discussion, and finally the paper ends with a conclusion.

Experimental

Construction of textile transmission lines

In this study, conductive yarns (stainless steel, silver plated PA and insulated copper) with different linear resistance values were used to create a transmission line in a textile structure. ***Figure 1*** shows the position of the conductive tracks in a woven sample. Conductive yarns were positioned in the middle of the fabric, having a straight trajectory without undulation. Thus in each sample the same conductive yarn was inserted four times in the weft direction during the weaving process at different distance intervals to obtain electrical connection points. The intervals for the insertion of conductive yarns (track intervals) were arranged to observe chemical affects after finishing treatments. Each sample was produced with a length of 40 cm and width of 5 cm. Since the conductive yarns were inserted horizontally without any undulation in the structure, their lengths in the structure were approximately 40 cm as well.

To produce e-fabric samples containing transmission lines, 100% cotton with a yarn count of 44/1 dtex was used as warp and weft yarn in the woven fabric for the non- conductive area in the structure. The e-fabric structures chosen were of plain, twill (3/1S) and sateen (4/1) weave in order to determine if there is any significant effect on the signal transferring capability of transmission lines after chemical treatments. Characteristics of the conductive yarns used as transmission lines are presented in ***Table 1***. For this study, a total of 165 e-fabric samples were produced containing three different weave types, 11 different conductive yarns and four different pretreatment processes with the control group.

The linear resistance of a conductive yarn is a measure of its opposition to the passage of electric current in a specified length [27]. The linear resistance of the conductive yarns was measured in ohms per meter in Ω/m using a Keithley® multimeter (from Keithley Instruments Inc., USA).

Pretreatment processes applied to e-fabric samples

Four sets of greige 100% cotton e-fabric specimens were subjected to combined pretreatment processes, except the untreated control group. The intent of our study was to determine if there is any significant difference in the signal transferring capability of e-fabric samples when they are subjected to different pretreatment processes.

First all the e-fabric samples were sized with a 100% starch sizing agent before the pretreatment processes, and then they were subjected to various pretreatment combinations, as summarised in ***Table 2***. Desizing, alkaline scouring and hydrogen peroxide bleaching of the fabrics were performed in a jet dyeing machine at a liquor ratio of 25:1. The conditions and ingredients for the pretreatment processes applied to the e-fabric samples are given in ***Table 3***. Alkaline scouring was conducted with 3 g/l of sodium hyroxide, 2 g/l of soda and 2 g/l the wetting agent at 95 °C for 45 min. Hydrogen peroxide bleaching was performed using 3 g/l of hydrogen peroxide (H_2O_2), 1 g/l of peroxide stabiliser, 1 g/L of the wetting agent and 3 g/l of caustic soda at 90 °C for 90 min. 2g/l of amylase and 2 g/l of the wetting agent were used for desizing of the samples at 95 °C for 45 min.

Table 2. *Process combinations.*

Process no.	Processes applied
1	Bleaching
2	Desizing+Bleaching
3	Scouring+Bleaching
4	Desizing+Scouring+Bleaching

Measurement procedure

Measurements were performed using a Tektronix® TDS 2012B oscilloscope (USA) and TekoPIC programming experimental kit (from Tekoelektronik Ltd., Turkey) as shown in ***Figure 2***. During the measurements, the TekoPIC experimental kit was firstly connected to the e-fabric samples to achieve electrical signal generation over the transmission lines. The electrical signal generated by the TekoPIC was constant, with a fixed magnitude (amplitude of 5V) flowing in a continuous steady state direction in order to observe the noisy signal easily. Then the oscilloscope was connected to the transmission lines of the samples in order to observe electrical signal waveforms, schematically represented in ***Figure 3***. For the electrical connections between transmission lines, with the TekoPIC used as a signal generator, as well as with the oscilloscope, crocodile jaws were used. Afterwards the signals obtained over the transmission lines were directly transferred and recorded on a computer for signal analysis. It should be here noted that the lines in the textile structure tested were used to transmit only constant signals with low amplitudes; besides this they are also capable of transmitting low frequency signals. All tests were carried out in laboratory conditions (20 °C and 65% RH).

Signal analysis

The signal extracted from the oscilloscope was in its raw form, meaning it was in an unprocessed state and contained substantial electrical noise. For instance, ***Figure 4*** shows a signal recorded over the 1st track of the transmission line of sample no. 9. Indeed the electrical noise, an unwanted electrical signal, obtained over the transmission lines increased the difficulty of detection of the signal of interest and this leads to a decrease in signal quality and a lower signal transferring capability as well [28]. Thus in order to make any reasonable comparison of the signal transferring capability of the e-fabric samples that were subjected to different pretreatment processes, the signals recorded were analysed using Matlab® R2010b software and their SNRs values calculated.

Signal to noise calculation

Essentially the SNR (signal to noise ratio) is the ratio of the signal of interest (signal power) to the undesirable signal (noise power) [29]. The SNR can be estimated by calculating the ratio of signal to noise power. In our study, once the signal was recorded, the noise level (unwanted signal) and amplitude were determined by signal processing in MATLAB®. Since the signal and noise were measured at the same impedance, the SNR was obtained by calculating the square of the amplitude ratio, where A is the root mean square (RMS) amplitude:

$$SNR = \left(\frac{A_{signal}}{A_{noise}}\right)^2$$

Generally SNRs are expressed in the logarithmic decibel scale. In electronics, the decibel is a convenient way for engineers to describe the input to output ratios of either power or voltages. Therefore in order to quantify the signal quality of each sample, the SNR_{dB} value of each sample was calculated using the following equations [27].

$$SNR_{dB} = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) = P_{signal,dB} - P_{noise,dB},$$

$$SNR_{dB} = 10\log_{10}\left(\frac{A_{signal}}{A_{noise}}\right)^2 = 20\log_{10}\left(\frac{A_{signal}}{A_{noise}}\right)$$

Table 3. *Recipes for pretreatment processes.*

Treatment process	Recipe	Process temperature, °C	Process duration, min
Desizing	amylase 2 g/l wetting agent 2 g/l	95	45
Scouring	wetting agent 2 g/l NaOH 3 g/l soda 2 g/l		
Bleaching	Hydrogen peroxide (H_2O_2) 3 g/l Peroxide stabilizer 1 g/l Wetting agent 1 g/l Caustic soda 3 g/l	90	90

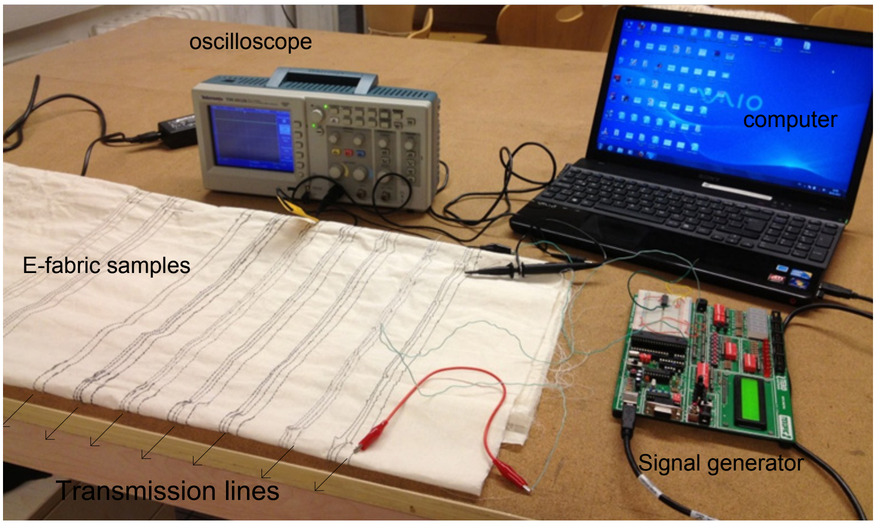

Figure 2. *Measurement set-up.*

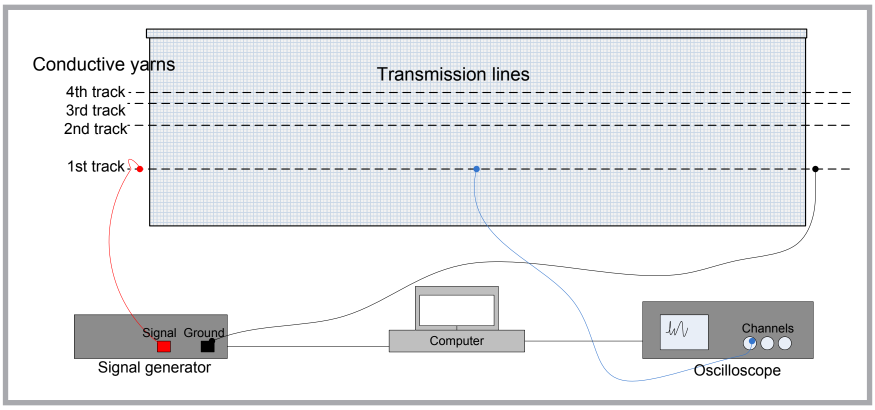

Figure 3. *Graphical representation for electrical connections.*

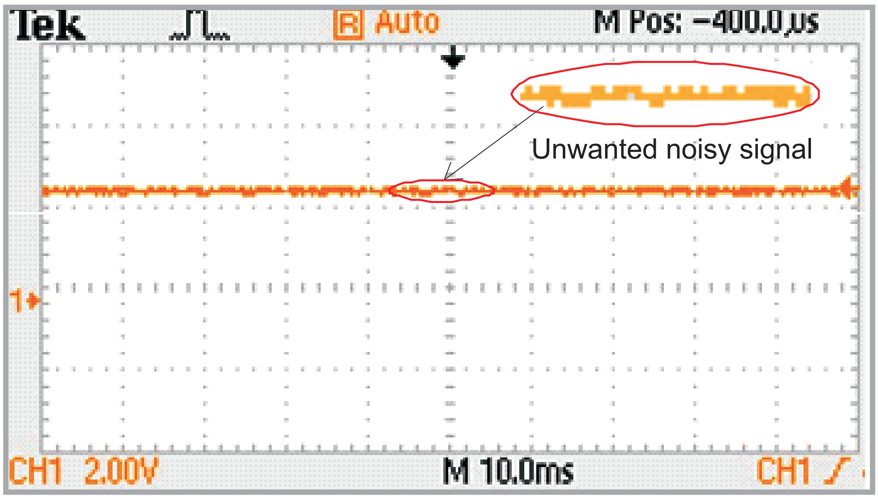

Figure 4. *Signal recorded over the 1st track of the transmission line of yarn sample no. 9 by the oscilloscope.*

A higher SNR value is indicative of better signal quality and less noise, which is preferred.

During calculations, the weave type, conductive yarn type, and pretreatment applied were noted. For each calculation, 2500 data were taken for one signal transfer, from which the mean SNRs of each weave type and conductive yarn type were calculated for each stage of the pretreatment process by taking into account the control group.

The results of signal analyses were used to evaluate the signal transferring capability of the samples in relation to conductive yarn type, weave type and pretreatment process applied. Repeated ANOVA measurements were made to assess any deterioration in the signal transferring capability of the conductive yarn types and weave types at all stage of the pretreatment processes. Additionally repeated ANOVA measurements were made to assess the interaction between the conductive yarn type and linear resistance values. Statistical analyses were carried out using SPSS®. The significance was accepted at $p < 0.05$ concerning the repeated ANOVA measurements.

Results and discussion

The first purpose of the current investigation was to determine differences in the signal transferring capability of e-fabric structures after pretreatment processes. The aforementioned objective was assessed specifically through consideration of three particular issues concerning comparisons between applied pretreatment processes (I. bleaching, II. desizing and bleaching, III. scouring and bleaching, IV. desizing and scouring and bleaching). Thus the majority of the results section concerns the following sections: assessment of the signal transferring capability of the e-fabric structures in relation to the textile pretreatment processes, assessment of the signal transferring capability in relation to the conductive yarn type, and assessment of the signal transferring capability due to the weave type. In the figures, terms indicating the process treatments {Bl, De+Bl, Sc+Bl, De+Sc+Bl} correspond to the pretreatments applied;
Bl = Bleaching,
De+Bl = Desizing+Bleaching,
Sc+Bl = Scouring+Bleaching,
De+Sc+Bl=Desizing+Scouring+Bleaching.

Table 4. *SNR computation.*

Yarn		**Amplitute. V**														
		Reference			**Bleaching**			**Desizing + Bleaching**			**Scouring + Bleaching**			**Desizing + Scouring + Bleaching**		
		Plain	**Twill**	**Sateen**	**Plain**	**Twill**	**Sateen**	**Plain**	**Twill**	**Sateen**	**Plain**	**Twill**	**Sateen**	**Plain**	**Twill**	**Sateen**
1	Signal_{RMS}	4.7927	4.7828	4.7910	4.8112	4.7541	4.7710	4.7680	4.7403	4.7520	4.7520	4.7730	4.7650	4.7320	4.7143	4.7210
	Noise_{RMS}	0.0231	0.0400	0.0321	0.0157	0.0322	0.0243	0.0379	0.0423	0.0365	0.0370	0.0406	0.0398	0.0432	0.0469	0.0456
2	Signal_{RMS}	4.7891	4.7844	4.7820	4.8140	4.7970	4.8010	4.7650	4.7529	4.7540	4.7541	4.7660	4.7640	4.7210	4.7123	4.7170
	Noise_{RMS}	0.0274	0.0399	0.0354	0.0185	0.0318	0.0276	0.0399	0.0447	0.0421	0.0409	0.0395	0.0395	0.0445	0.0457	0.0467
3	Signal_{RMS}	4.7909	4.7655	4.7840	4.8040	4.7966	4.7904	4.7420	4.7229	4.7380	4.7542	4.7134	4.7380	4.7210	4.7012	4.7130
	Noise_{RMS}	0.0272	0.0399	0.0342	0.0191	0.0322	0.0265	0.0396	0.0457	0.0421	0.0387	0.0431	0.0412	0.0487	0.0496	0.0492
4	Signal_{RMS}	4.7832	4.7643	4.7740	4.8013	4.7969	4.7968	4.7430	4.7254	4.7420	4.7412	4.7321	4.7340	4.7020	4.6950	4.6960
	Noise_{RMS}	0.0288	0.0409	0.0354	0.0195	0.0307	0.0254	0.0396	0.0447	0.0412	0.0383	0.0387	0.0379	0.0511	0.0534	0.0523
5	Signal_{RMS}	4.7832	4.7623	4.7780	4.8021	4.7865	4.7905	4.7407	4.7230	4.7380	4.7434	4.7040	4.7320	4.7012	4.7021	4.7010
	Noise_{RMS}	0.0334	0.0405	0.0376	0.0205	0.0306	0.0280	0.0398	0.0478	0.0451	0.0389	0.0394	0.0398	0.0490	0.0547	0.0560
6	Signal_{RMS}	4.7831	4.7612	4.7720	4.8013	4.7853	4.7970	4.7324	4.7200	4.7240	4.7434	4.7213	4.7310	4.7056	4.7012	4.7020
	Noise_{RMS}	0.0326	0.0403	0.0365	0.0211	0.0302	0.0268	0.0400	0.0472	0.0453	0.0374	0.0451	0.0432	0.0501	0.0547	0.0544
7	Signal_{RMS}	4.7750	4.7582	4.7650	4.7930	4.7859	4.7850	4.7363	4.7210	4.7260	4.7427	4.7340	4.7412	4.6970	4.6950	4.6890
	Noise_{RMS}	0.0331	0.0412	0.0376	0.0228	0.0321	0.0267	0.0402	0.0488	0.0456	0.0403	0.0471	0.0453	0.0543	0.0565	0.0587
8	Signal_{RMS}	4.7750	4.7542	4.7660	4.7912	4.7880	4.7894	4.7214	4.7120	4.7170	4.7357	4.7230	4.7230	4.6780	4.6980	4.6850
	Noise_{RMS}	0.0335	0.0415	0.0365	0.0231	0.0343	0.0287	0.0414	0.0478	0.0453	0.0409	0.0464	0.0432	0.0567	0.0588	0.0589
9	Signal_{RMS}	4.7620	4.7210	4.7450	4.7845	4.7773	4.7789	4.7022	4.6850	4.6960	4.7157	4.6940	4.7010	4.6570	4.6670	4.6350
	Noise_{RMS}	0.0346	0.0431	0.0387	0.0240	0.0351	0.0378	0.0444	0.0511	0.0467	0.0456	0.0532	0.0497	0.0533	0.0596	0.0567
10	Signal_{RMS}	4.7231	4.6830	4.6970	4.7654	4.7443	4.7543	4.6650	4.6350	4.6510	4.6570	4.6245	4.6420	4.6540	4.6320	4.6450
	Noise_{RMS}	0.0366	0.0451	0.0412	0.0270	0.0361	0.0321	0.0465	0.0533	0.0512	0.0450	0.0522	0.0498	0.0580	0.0621	0.0611
11	Signal_{RMS}	4.7043	4.6510	4.6740	4.7263	4.7241	4.7130	4.6430	4.6145	4.6230	4.6310	4.6013	4.6210	4.5940	4.5834	4.6020
	Noise_{RMS}	0.0401	0.0481	0.0463	0.0300	0.0423	0.0377	0.0485	0.0565	0.0530	0.0501	0.0543	0.0521	0.0643	0.0656	0.0650

Terms indicating weave type {P, T, S} show the plain, twill and sateen fabric structure, respectively.

Signal transferring capability in relation to pretreatment processes applied

The results of SNR computations are presented in ***Table 4***. It is observed that samples treated with only the bleaching process have a higher signal amplitude and lower noise amplitude than those treated with desizing+bleaching, scouring+bleaching, and desizing+scouring+bleaching (see ***Table 4***). In addition to that, samples desized, scoured and bleached (process no. 4) have a lower signal transferring capability than for the other processes. For instance, ***Figure 5*** shows the SNRs of plain e-fabrics subjected to pretreatment processes. It is evident from ***Figure 5*** that increasing the number of pretreatment processes applied results in decreased SNR values. In other words, e-fabrics subjected to more pretreatments (e.g. fabrics subjected to desizing+scouring+bleaching rather than being subjected to desizing+bleaching or scouring+bleaching) showed worse signal transferring capability, which was expected, as the number of pretreatments increased, deformation of the fabrics occurred. The place where deformation occurs is in the individual fibres and conductive yarns, both of which are capable of causing movement and damage within the woven fabric structures, possibly resulting in surface cracks on the conductive yarns as well as deformation over the transmission lines. This would effectively lead to a higher electrical resistance and reduce the quality of the signal over the transmission lines. With reference to ***Table 4***, it was also found that bleaching generally caused an increase in the ratio of the signal amplitude to noise amplitude when compared with reference values, which may be attributed to the chemicals used in the bleaching process, which may improve the signal transmission properties of e-fabrics since the temperature and duration for all processes are similar. However, as the interactions of chemicals widely differ from each other, a more intensive study on chemicals for signal transmission properties is essential.

In addition to the signal analysis results, the statistical analysis also indicated that there was a significant difference

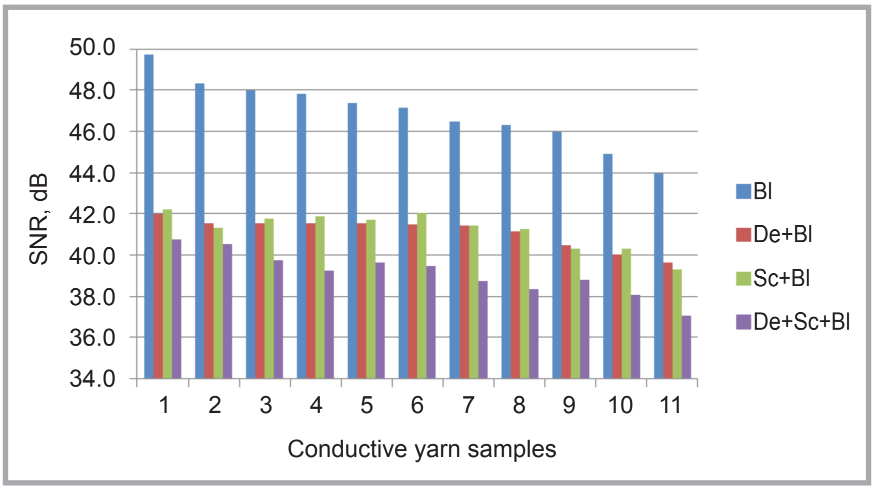

Figure 5. *SNRs of plain e-fabrics subjected to pretreatment processes.*

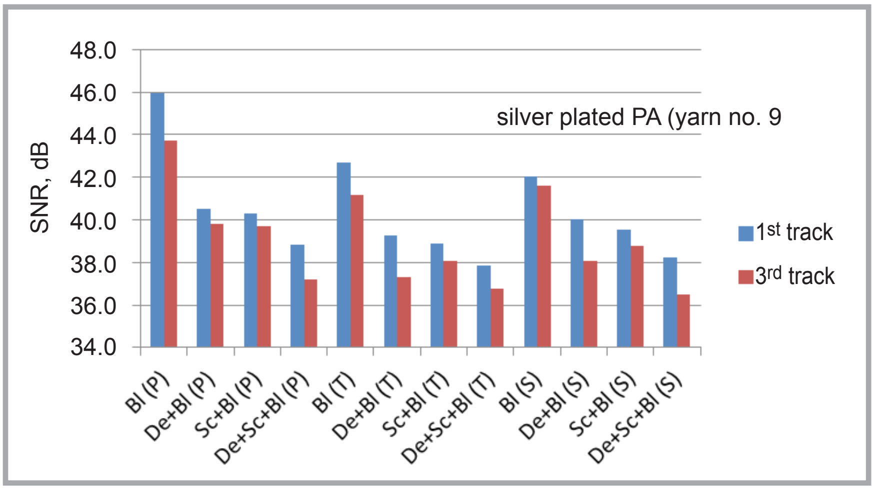

Figure 6. *Comparison of transmission line tracks (yarn type: silver plated PA no. 9).*

Table 5. *Signal interactions for bleached plain fabric sample containing yarn no. 5*

	Sample yarn no. 5-stainless steel (45 ohm/m)	SNRs observed in track			
		1st	2nd	3rd	4th
signal transmission over tracks	signal passing from 1st track	47.40	-	-	-
	signals passing from 1st and 2nd track	45.55	44.71	-	-
	signals passing from 1st, 2nd and 3rd track	42.39	41.25	39.18	-
	signals passing from 1st, 2nd, 3rd, and 4th track	43.69	39.99	40.53	39.81

Table 6. *Signal interactions for bleached plain fabric sample containing yarn no. 7.*

	Sample yarn no. 7-silverplated PA (50 ohm/m)	SNRs observed in track			
		1st	2nd	3rd	4th
signal transmission over tracks	signal passing from 1st track	46.45	-	-	-
	signals passing from 1st and 2nd track	43.95	43.32	-	-
	signals passing from 1st, 2nd and 3rd track	42.31	40.38	40.69	-
	signals passing from 1st, 2nd, 3rd, and 4th track	41.02	39.64	38.76	40.19

Table 7. *Signal interactions for bleached plain fabric sample containing yarn no. 11.*

	Sample yarn no. 11-silverplated PA (2000 ohm/m)	SNRs observed in track			
		1st	2nd	3rd	4th
signal transmission over tracks	signal passing from 1st track	43.93	-	-	-
	signals passing from 1st and 2nd track	41.21	40.81	-	-
	signals passing from 1st, 2nd and 3rd track	40.69	41.26	40.85	-
	signals passing from 1st, 2nd, 3rd, and 4th track	39.90	38.18	38.14	38.23

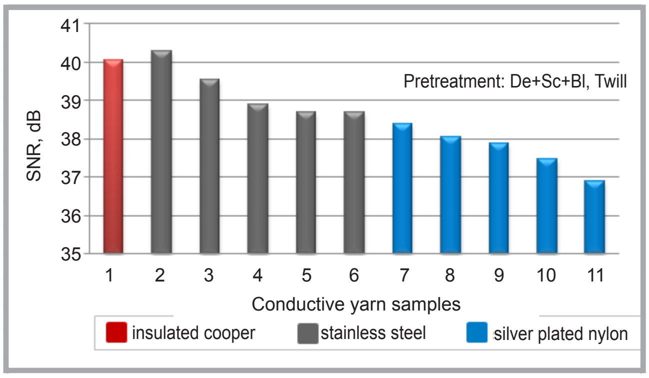

Figure 7. Comparison of SNRs in relation to conductive yarn type for e-fabric samples subjected to desizing+scouring+bleaching processes.

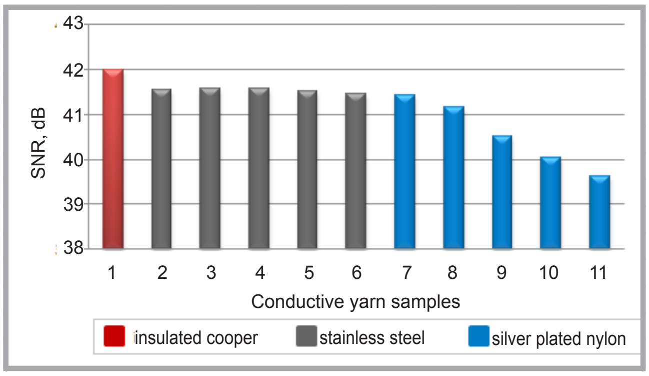

Figure 8. Comparison of SNRs in relation to conductive yarn type for e-fabric samples subjected to desizing+ bleaching processes.

between the pretreated e-fabric samples with respect to the signal transferring capability at a p-value of 0.000 (< 0.05 ANOVA). This means the pretreatment processes significantly influenced the signal transmission properties of the e-fabric samples.

Due to material characteristics, conductive yarns woven extremely close to each other may create an undesirable effect on one another when they are transmitting signals [30]. In addition to that, ion change may occur during the chemical processes and influence the transmission capability of the tracks positioned extremely close to each other. Thus the SNR levels of the transmission lines may also differ due to their position in the fabric. For instance, ***Figure 6*** shows a comparison of SNRs obtained at the 1st and 3rd tracks of the e-fabric samples. Our results showed that after each pretreatment process and for each type of weave construction, the SNRs obtained at the 3rd track of the transmission lines positioned between two conductive yarns extremely close to each other (see ***Figure 1***), are slightly lower than the SNRs obtained at the 1st track of the transmission lines. The ion change and easy deformation of tracks positioned so close to each other, due to frictional stresses in the chemical treatments, would be responsible for the phenomena observed.

In addition to these results, the influence of signal interactions was also investigated. Since the plain samples treated with the bleaching process presented better SNR results compared to other samples, their signal interactions when transmitting one, two, three and four signals together were studied. For instance, ***Tables 5 - 7*** show the SNR values observed over the transmission tracks for transmission lines made of conductive yarn 5, 7 and 11. In the tables, since conductive yarns nos. 5 and 7 have similar linear resistance values (45 ohm/m and 50 ohm/m) and are composed of different materials (stainless steel and silver plated PA), they were chosen for comparison. Additionally since conductive yarn no. 11 has the highest linear resistance value among conductive yarn samples, it was also selected to observe if there was asignificant difference between signal interactions. As presented in the Tables, all transmission tracks were subjected to signals generated sequentially, and signals passing through the conductive tracks were observed one by one.

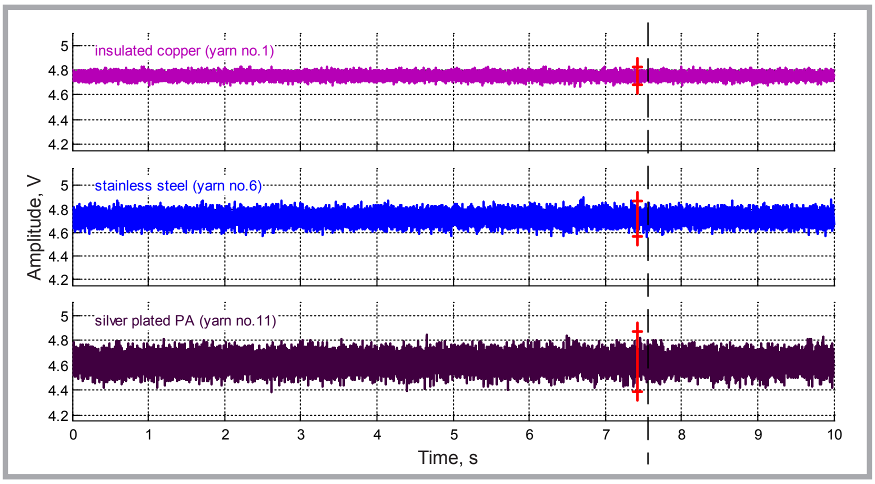

Figure 9. Comparison of signals obtained over transmission lines designed with insulated copper, stainless steel and silver plated PA for sateen e-fabric samples desized + bleached.

With reference to ***Tables 5 - 7***, it is generally observed that the SNR values of tracks composed of stainless steel yarns are a bit higher than those of silver plated yarns. In other words, transmission lines created with stainless steel showed better signal quality than those created with silver plated yarns. The worst SNRs were obtained with conductive yarn no. 11, which would probably be due to the higher linear resistance values. When the signal interactions were investigated, it was found that when there is only one signal passing through one conductive track, the SNRs obtained over the transmission line are higher. However, as the number of signal transmissions increases on the sample, such that where two, three and even four signals are transmitted from the 2nd, 3rd, and 4th conductive tracks, respectively, the SNRs values decrease. In other words, when only one signal is carried by the transmission line, the signal transferring capability or signal quality of the line is better. This may be attributed to the fact that as the conductive tracks are positioned extremely close to each other, they may create an undesirable effect on one another when they are transmitting signals. This undesired phenomenon possibly results in a crosstalk effect or slightly noisy data on the transmission lines, hence causing a decrease in signal quality. As proven by ***Tables 5 - 7***, when there are four signals carried by four transmission tracks, the

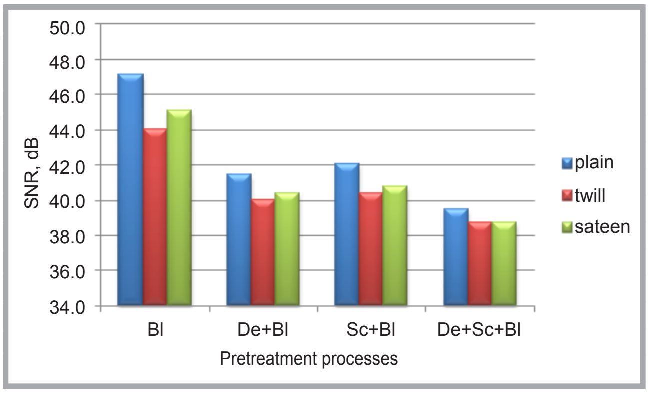

Figure 10. Comparison of SNR values according to weave type for e-fabric samples containing stainless steel (yarn no. 6).

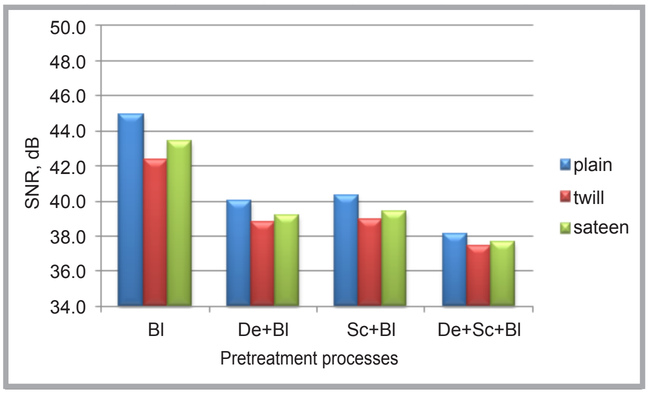

Figure 11. Comparison of SNR values according to weave type for e-fabric samples containing silver plated PA (yarn no. 10).

SNR values observed over the four conductive tracks are generally lower than those carrying one, two and three signals.

Signal transferring capability in relation to conductive yarn type

Figures** 7* and ***8 show a comparison of SNRs in relation to the conductive yarn type for samples subjected to different pretreatment processes. It is possible to notice that the SNR values of stainless steel and silver plated PA yarns are apparently different from each other (see ***Figures** 7* and ***8***). From the results it is generally observed that SNR values of transmission lines designed with stainless steel are higher than those of transmission lines designed with silver plated PA. This means that transmission lines created with stainless steel showed better signal quality than those created with silver plated yarns. A similar conclusion explaining the good performance of stainless steel yarns compared to silver coated yarns was also reported in literature [1, 31].

Moreover, ***Figure 9*** shows a comparison of signals obtained over transmission lines designed with insulated copper (yarn no. 1), stainless steel (yarn no. 6) and silver plated PA (yarn no. 11) for the sateen e-fabric sample desized + bleached. It was found that changes in the signal amplitude from the highest to lowest are insulated copper (linear resistance <5 ohm/m), stainless steel (linear resistance <60 ohm/m) and then silver plated PA (linear resistance < 2000 ohm/m). Besides this, when the noise amplitudes are compared (see also ***Table 4***), the change in noise amplitude was low ($\text{noise}_{\text{RMS}}$ amplitude = 0.0365) with insulated copper (liner resistance <5 ohm/m), whereas it was high ($\text{noise}_{\text{RMS}}$ amplitude = 0.053) with silver plated PA (linear resistance < 2000 ohm/m). From the morphology and amplitudes of signals, these differences permit us to state that as the linear resistance of the yarn increases, the noise level also rises. Additionally considering the SNR values obtained, it can also be concluded that the change in SNRs is proportional to the linear resistance of the yarns, which means that when the conductivity of the yarn increases, the noise level decreases, resulting in better signal transferring capability, as previously mentioned in literature [27].

Apart from the signal analysis results, statistical analysis also revealed that SNR values of the conductive yarn types, namely stainless steel, silver plated nylon and insulated copper, are significantly different with the p-value of 0.001 (< 0.05 ANOVA). Additionally when the analysis was performed considering linear resistances of the conductive yarns, it was also found that the linear resistance significantly influences the signal transferring capability of transmission lines at a p-value of 0.04 (< 0.05 ANOVA).

Signal transferring capability in relation to weave type

It is evident from ***Figures 10*** and ***11*** that the plain weave type showed higher SNR values than the twill and sateen weave types. In other words, the signal transferring capability of plain e-fabrics is better as compared to twill (3/1S) and sateen (4/1) e-fabrics. The reason may be attributed to a change in the displacement of weft and warp yarns positioned in the fabric structure. Since the weft and warp replacement passage during weaving are higher in a plain weave, the conductive fibres are better integrated in the body of the fabric, and hence during the chemical processes this may led to lesser deformation or fewer surface cracks on the conductive yarns passing through the fabric structure, as well as on transmission lines.

Moreover according to ANOVA statistical analysis, it was found that there was a significant difference between weave types at a p-value of 0.011 (< 0.05). All these findings indicate that the weave type also has a considerable effect on the signal transferring capability of transmission lines.

Conclusion

The influence of pretreatment processes on the signal transferring capability of transmission lines constructed using different conductive yarns in various weave patterns was tested by performing signal to noise measurements before and after each pretreatment process, namely bleaching, desizing+bleaching, scouring+bleaching, and desizing+scouring+bleaching.

The results reported in this work show that pretreatment processes significantly influence the signal transferring capability of transmission lines. The e-fabric samples subjected to only the bleaching process have a higher signal amplitude and lower noise amplitude than those treated with desizing+bleaching, scouring+bleaching, and desizing+scouring+bleaching. However, as the number of pretreatments was increased, it was observed that the signal quality of the transmission lines decreased, which is probably due to the fact that an increase in the number of pretreatment processes causes damage to the e-fabric or possibly results in surface cracks on the conductive yarns, which would effectively lead to higher electrical resistance and reduce the quality of the signal over the transmission lines. Therefore it can be stated that to create transmission lines in a fabric with the weaving process and then to apply a pre-treatment process prior to dyeing is not a suitable way to obtain reliable signal transmission over the e-fabrics for electronic textile applications. Additionally it was found that the linear resistance of conductive yarns and the type of weave structure significantly affect the signal transferring capability of transmission lines. As the linear resistance increases, the signal transferring capability of the transmission lines decreases. From the results, stainless steel yarns performed better than silver coated yarns due to the fact that it can transmit signals at a higher signal amplitude and with lower noise. In fact plain e-fabrics were found to achieve higher SNR values compared to twill and sateen ones.

For future research work, different types of signal waveforms such as square, saw-tooth, triangle etc. with different frequencies can be applied to transmission lines to investigate their signal transferring behaviour.

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