

# Electrical Characterization of Conductive Ink Layers on Textile Fabrics: Model and Experimental Results

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## Abstract.

This paper presents a novel strategy for the integration of microelectronics in textile. A sheet resistive medium is proposed. It consists of a textile coated with a conductive ink that allows the power supply of the transceivers and their communication. Thanks to the sheet configuration, the positioning of transceivers is 2D and the fault tolerance to the aging caused by the use, is very high. The medium is characterized, and a model is proposed to predict the resistance between two points as a function of their positions. Experimental results are presented that shows an agreement better than 2.34 % between the model and the real measures of the resistance.

## 1. Introduction

Electro-textiles (or e-textiles) are becoming an emerging field in industry. The possibilities that this technology holds seem almost limitless. Currently, e-textiles are being developed for many applications and markets, including biomedical sensing, wearable computing, large area sensors and large area actuating devices [1]. Once developed, these concepts will be readily applicable to many existing products and can open new chances in new markets for textiles. In a world which is becoming rapidly interconnected by technology, the addition of e-textile components to everyday products, as well as specifically targeted designs will provide the ability to enhance product performance and provide new and unique services to customers.

Textiles are inherent microstructures with fantastic properties: they are flexible and much more mechanically stable than foils. However, until now we did not have the right materials and techniques or we applied the wrong materials or techniques in attempts to use textile structures as electro-textiles in some ways and even as parts of a microelectronic structure.

Conductivity over fabrics is one of the challenges in electro-textiles, different materials and ways are available: carbon black, some metals and recently conductive polymers are currently engineered in the market as fibers, yarns, pastes, etc [2]. that could be

applied to fabrics by different standard techniques: weaving, knitting, coating, laminating, printing, etc. [3]. Some of these techniques are not versatile to achieve stable and homogeneous conductive tracks or surfaces with a predefined geometry. Mainly some attempts has been tried to trace conductive tracks with high conductivity by weaving monofilament conductive metal yarns [4] and recently other attempts involved techniques used in printed flexible electronics over fabrics by using conductive inks or pastes [5]. Conductive tracks over fabrics by weaving monofilament metallic yarns [4] or by printing conductive inks over pre-engineered fabrics substrates [5] could be and alternative to network electronic devices attached on textiles, however it provides new problems caused by the everyday use involving textile products which can break the tracks, and using this integrated routed approach can also therefore become more awkward in applications where the accurate location of these devices is essential depending on the user and application.

This paper focuses on the use of layers instead of tracks, to carry data and power over clothing by printing or coating conductive ink layers on textile fabrics. This can expand the network over flexible two-dimensional planes rather than wires, and results in the distribution of the network over the entire surface of the textile, preventing the cracking caused by everyday use and allowing the location of electronic devices attached [6][7]. In that way, to characterize the electrical properties of such layers to check its capabilities as a physical media to transmit power and information appears as a necessity and is the content of this paper. It is divided in the following parts: section 2 introduces the concept and advantages of the conductive inks printed in layers over textile fabrics. Section 3 is devoted to present the parameters that characterize the electrical properties of one implementation of such layers with conductive ink, as well as a model to predict the resistance between any two points of a rectangular sheet. Section 4 presents the results of measurements of the resistance between two points on three samples of the same conductive ink over three fabrics, and finally section 5 concludes the paper.

## 2. Conductive Ink on Textile Fabrics

The manufacture of flexible printed circuits is one segment of the electronics industry in which new materials are enabling an ever-widening variety of products and devices. At the heart of many new designs are highly conductive silver, carbon or conductive polymer inks that allow engineers to develop smaller, more powerful electronics that can be manufactured in some footprints.

Recently has been developed conductive flexible inks (flexible and stable against stress), which are good candidates to achieve conductivity easily screen printed over pre-engineered textile fabrics [8]. Some flexible and stable conductive inks based on metals, carbon and conductive polymers has been used on this experimentation screen printed over knitted and woven pre-engineered fabrics coated by novelty coating methods to achieve a regular surface.

### 2.1. The Layer Approach

The goal is to use the conductive layer as a power as well as a data transmission mean. The relatively reduced electrical conductivity of the conductive layer, which is a drawback from the data transmission point of view, may be a potential solution to integrate in a single network the power and communication needs of the different parts of the system. In principle, many arrangements are possible: from autonomous transmitter/receivers with independent power storage to a centralized network with a unique battery to provide power to any connected equipment. Figure 1(a) shows a sketch of a possible arrangement: it has a transmitter T, a receiver R and a battery B. The internal impedance of such elements is not shown in the figure. Every piece of the system is connected to the two planes of conductive material at both sides of a sheet of a textile dielectric. The battery supplies power to both, transmitter and receiver. Signals from the transmitter propagate through the conductive layers reaching the receiver, which reacts properly. This arrangement has the advantage that an independent battery is not required for each component of the system. However, the connection of a battery in the conductive layers exerts a considerable influence on the transmission properties. Figure 1(b) shows the electrical equivalent circuit for this configuration at low frequency. The electrical properties of the planes are: the sheet resistance  $r$  [ $\Omega/\text{square}$ ] and the capacitance per unit area  $c$  [ $\text{pF}/\text{cm}^2$ ] which are a function of the material and thickness of the conductive and dielectric layers. At low frequency the effective resistance (represented by the resistors  $R_{xx}^{yy}$ ) is the main contribution to the impedance between each circuit component. The value of such effective resistances depends on the

distance between T, B and R, as well as their location in the plane and also depends on  $r$ . At higher frequencies the reactive part of the impedance have to be taken into account and the distributed nature of  $r$  and  $c$  makes it impossible to represent in a simple circuit with lumped resistance and capacitance the electrical equivalent of the system shown in Figure 1(a).

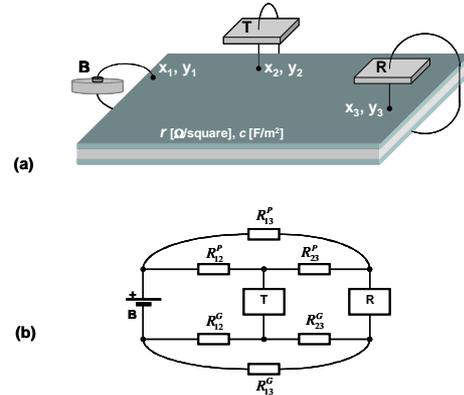


Figure 1. (a) Target configuration. (b) Low frequency equivalent electrical circuit of the configuration.

## 3. Electrical Characterization

To characterize the conductive layers on textile fabrics the first step is to measure  $r$  and  $c$ . We have performed such measurement on three samples of layers of black carbon over different textile fabrics. Sample 1 is a polyester plain knitted fabric 28 gauge coated by breathable polyurethane 65  $\text{g}/\text{m}^2$  bright finish, sample 2 is a polyester plain knitted fabric 28 gauge coated by breathable polyurethane 75  $\text{g}/\text{m}^2$  bright finish and sample 3 is a polyester plain knitted fabric 28 gauge coated by breathable polyurethane 65  $\text{g}/\text{m}^2$  superbright finish. The conductive layers in all samples is conductive carbon ink Acheson Electrodag 965SS [9]. Table I summarizes the relevant parameters of the textiles samples.

Table I. Description of the Measured Samples.

Sample	Conductive ink	Fabrics	Coating	Length (mm)	Width (mm)
1	Acheson Electrodag 965SS	Plain Knit	Polyurethane coated bright	275	193
2	Acheson Electrodag 965SS	Plain Knit	Polyurethane coated bright	280	197
3	Acheson Electrodag 965SS	Plain Knit	Polyurethane coated Super bright	282	197

The manufacturing process includes the following steps: (a) knitting process, manufacturing of fabric with circular knitting machine, (b) Coating process, manufacturing of coating with polyurethane by

coating/laminating machine (c) Screen Printing Process, manufacturing of the conductive sheet with conductive carbon ink by Semiautomatic Screen Printing equipment. Figure 2 shows a photography of the three samples. As can be seen, due to a defect in the fabrication process, sample 3 has many voids in the conductive layer, which may mimic its state after real use. So, we did not reject such sample and also performed the measurements on it.

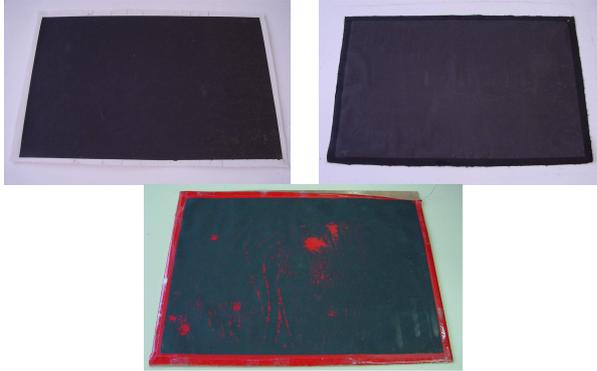


Figure 2. Left: sample 1, center: sample 3, right sample 2.

The measurements are performed with an Agilent 34401A multimeter (4 wires measurement) and a HP4284A LCR meter with a Kelvin probe. All measurements are made at room temperature. To know  $r$ , we measure the resistance between two copper planes in firm contact with the conductive ink. The resistance between the copper planes is recorded for different distances between the copper planes. For the measurement of  $c$ , we put the fabrics on top of a copper plane, thus making a condenser with one plate being the conductive layer and the other the copper plane. Then, we connect a terminal of the Kelvin probe to the copper plane and the other terminal to a copper cylindrical finger with a diameter of 6mm in contact with the conductive layer. The finger is placed at different locations to check the consistency of the measurements. Frequency is swept from 1KHz to 1MHz, and the applied voltage level is 1V. The results are shown in Table II.

Table II. Sheet resistance and capacitance per unit area of the three samples. \*\* see text

Sample	$r$ (average) [ $\Omega$ /square]	$r$ (stdev) [ $\Omega$ /square]	$c$ (average) [pF/cm <sup>2</sup> ]	$c$ (stdev) [pF/cm <sup>2</sup> ]
1	369.97	7.36	0.95	$8.1 \times 10^{-3}$
2	284.20**	41.34**	1.63	$1.66 \times 10^{-2}$
3	365.02**	48.13**	1.22	$1.36 \times 10^{-2}$

The conductive layer of samples 2 and 3 are not uniform, so the value of  $r$  in the table is taken as an average over the whole area and the standard deviation is a measure of this non uniformity. This subject will be widely discussed in the next section.

### 3.1 Modeling the Resistance Between Two Points of a Plane

In addition to the sheet resistance, to calculate the resistance between two points in a plane (like  $R_{xx}^P$  or  $R_{xx}^G$  in Figure 1) it is necessary to know their distance as well as the geometry of such plane. In general, and for complicated geometries, only numerical methods are able to perform such calculation. However if we restrict to a simple rectangular geometry it is only necessary to know the sheet resistance  $r$  of the conducting layer, which in this paper is assumed to be constant, the width  $W$  and length  $L$  of the rectangular plane and the location of the points between of which we want to know the resistance. The following paragraphs are devoted to present this method [10] and to compare its prediction with real measurements on the three samples described above.

Our problem is the calculation of a two-dimensional current flow. It is well known from the potential theory [11] that if we inject a current  $I$  to a contact at a long distance away from the plane boundary, the potential profile  $\phi(d)$  in the vicinity of the contact is found as

$$\phi(d) = -\frac{rI}{2\pi} \ln d + const. \quad (1)$$

where  $r$  is the sheet resistance of the plane, which here is assumed to be constant, and  $d$  is the distance to the contact. If there are  $N$  contacts, the potential within the plane is the sum of the potential contributed by the currents from each of the  $N$  contacts. Here we assume that the plane boundaries are far away from the contacts. In these conditions we have

$$V(p) = -\frac{r}{2\pi} \sum_{i=1}^N I_i \ln d_i + const. \quad (2)$$

where  $V(p)$  is the potential at the point  $p$  where it is measured,  $d_i$  is the distance between the contact  $i$  and point  $p$  and  $I_i$  is the current of contact  $i$ . The constant term is the potential far away from the contacts. If distances  $d_i$  are much larger than the size of contacts (we assume circular contacts of radius  $a_k$ ), the following set of simultaneous equations for the potential of each contact approximates (2) as

$$V_k = -\frac{r}{2\pi} \left( I_k \ln a_k + \sum_{i \neq k} I_i \ln d_{ik} \right) + const. \quad (3)$$

Expressions (3) and the Kirchhoff's current law

$$\sum_{i=1}^N I_i = 0 \quad (4)$$

can be organized in matrix form and solved for  $I_i$  when potentials  $V_k$  at the contacts are given [10]. After the currents  $I_i$  are known, the resistance between contacts is easily calculated using Ohm's law.

The output of a computer program implementing (3) and (4) have been compared with measurements of

resistance on the three samples described above. As the reasoning made in the previous paragraph assumes a plane of infinite extension, we take into account the effects of the finite plane boundaries by applying standard techniques of images from electrostatics [11].

#### 4. Measurements

For the measurements we place a cylindrical copper contact of radius equal to 3mm at a fixed place on the conducting plane. Then, an identical moving contact is placed at equally spaced locations over the layer surface and for each location the resistance between both contacts is recorded. For the two measurements of sample 1 the distance between each measurement point is 1 cm and 4 cm respectively, and for samples 2 and 3 is 2 cm.

Table III show the conditions of the measurements and Figures 3 to 8 show the results.

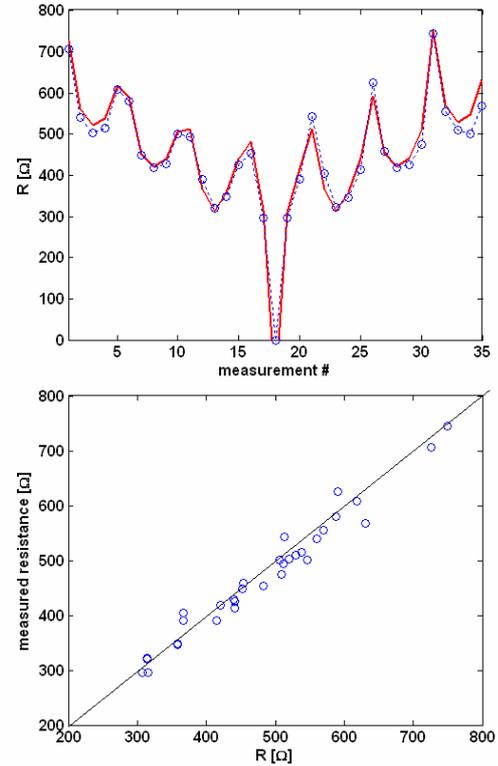
**Table III.** Location of reference point and number of equally spaced measurement points for each sample.  $X=0, Y=0$  is the bottom left corner of the sample.

Sample	Reference point X	Reference point Y	# points
1	140 mm	86 mm	5×7
1	4 mm	4 mm	20×26
2	140 mm	98.7 mm	9×13
3	140 mm	100 mm	9×14

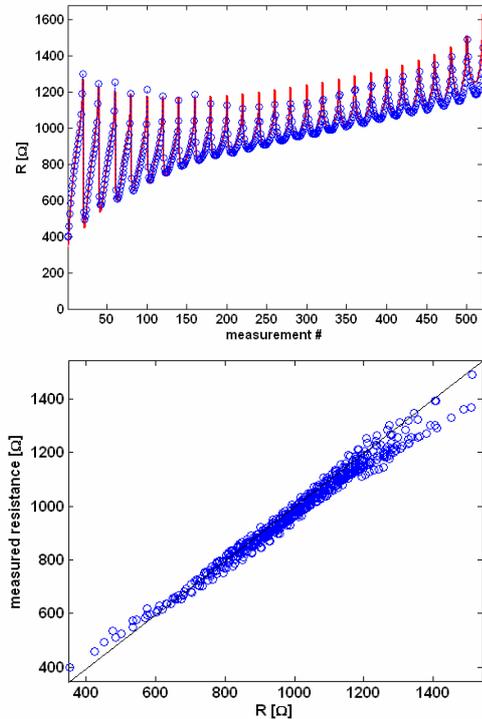
In all cases the measurement points are explored from bottom to top and from left to right. As can be seen in Figures 3 and 4, correlation between the measured and calculated values in sample 1 is good. The RMS error is 2.34 %. This is due to the uniform properties of the conducting plane and the absence of any damage in its surface. For the case of the centered reference point, the resistance shows a change from about  $300\Omega$  to  $750\Omega$  except for the points very close to it. When the reference point is at the bottom left corner, the resistance changes from about  $400\Omega$  to  $1500\Omega$ . These may be taken as limiting cases for the expected resistance between any two points of an uniform conducting plane of this material when the conducting sheet is on a new (not used) textile fabrics.

Results of sample 2 show an important change with regard to sample 1, as illustrated in Figures 5 and 6.

Figure 5 shows an asymmetry in the distribution of the resistance between the left and the right half plane. This asymmetry is confirmed in Figure 6 where we can see how the contours of equal resistance are not symmetric with respect to the reference point, but they are less closely spaced at the left side of the plane.



**Figure 3.** Sample 1, centered reference point. Top: Measured resistance (circles) vs. measurement point (solid line shows the calculated value). Bottom: correlation between measured and calculated resistance.



**Figure 4.** Sample 1, reference point at  $(X,Y) = (4,4)$  mm. Top: Measured resistance (circles) vs. measurement point (solid line shows the calculated value). Bottom: correlation between measured and calculated resistance.

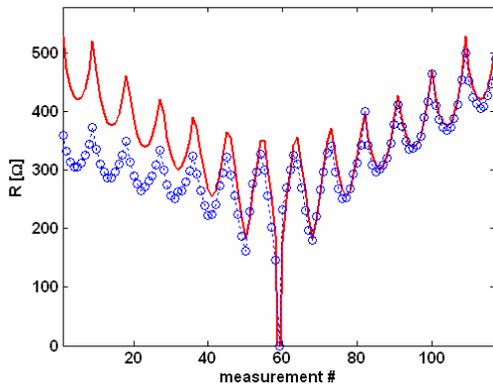


Figure 5. Sample 2, centered reference point. Measured resistance (circles) vs. measurement point (solid line shows the calculated values).

This phenomenon may be explained by the variation of sheet resistance along the plane. To highlight this, Table IV shows the values of the sheet resistance  $r$  of sample 2 in both directions: bottom to top and left to right when it is measured at six stripes of equal width but located in three places on the conducting plane.

Table IV. Sheet resistance of sample 2 as a function of position.

Sheet resistance [ $\Omega$ /square]			
Top stripe	236.7	Left stripe	246.2
Center stripe	254.6	Center stripe	278.2
Bottom stripe	222.6	Right stripe	328.2

As can be seen, the sheet resistance is greater at the right side and at the top of the plane than at the left and bottom side. As a consequence the correlation between calculated and measured values is not as good as in the case of constant  $r$ . For sample 2, the resistance between any two points of the plane ranges from about  $150\Omega$  to  $500\Omega$ , which are slightly lower values with respect sample 1. This fact may be explained for the lower average value of  $r$ .

Figures 7 and 8 shows the results for sample 3. In this case the conducting layer is damaged in many points due to a defect in the fabrication process of such sample. In some sense, we can take advantage of this fact as a check of what may happen after a given use of the textile fabrics. Sample 3 has a zone between the center and the right boundary with many spots and scrapes without conductive ink irregularly spread in the plane, and includes a big spot where the conducting ink is absent.

As a consequence, the resistance from the reference point, which is located close but not exactly, at the plane center, increases. In its turn, in the left side, the size and density of damages are lower and the discrepancies between calculated and measured values are smaller.

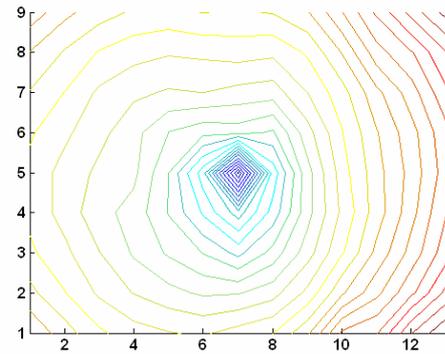
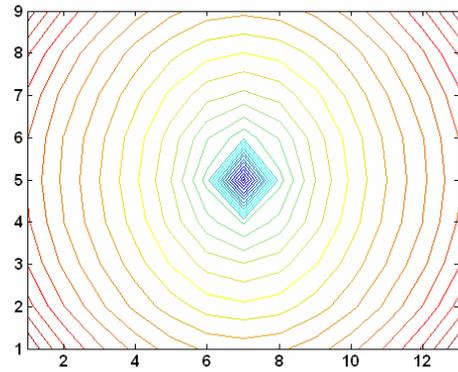


Figure 6. Sample 2. Contours of equal resistance. Top: calculated. Bottom: measured.

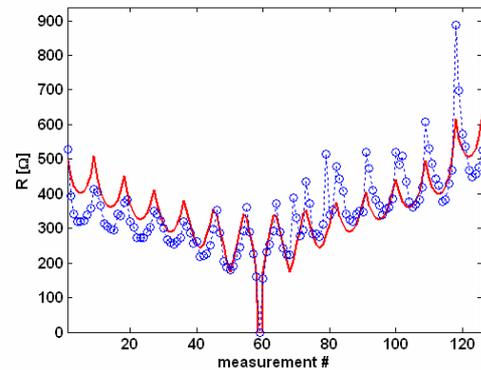


Figure 7. Sample 3, almost centred reference point. Measured resistance (circles) vs. measurement point (solid line shows the calculated values).

Observe how the larger differences in resistance are produced at the far ends of each series of measurements where the effect of all defects in the conducting paths between the reference and the measurement point accumulate, thus strongly increasing both, the absolute resistance and the range of their values (from about  $150\Omega$  to  $900\Omega$  in sample 3), thus almost doubling the expected maximum resistance.

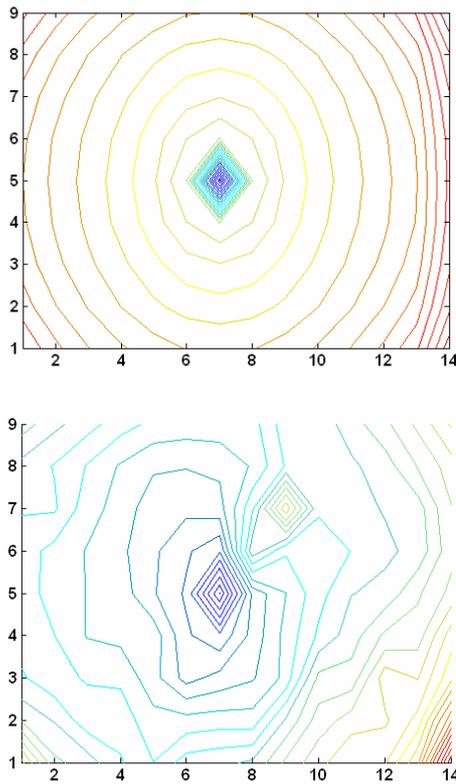


Figure 8. Sample 3. Contours of equal resistance. Top: calculated (no defects). Bottom: measured.

## 5. Conclusions

Sheets of conducting layers have potential advantages to solve the problem of interconnecting electronic equipment on textile fabrics. Different technologies of such conducting layers are available. The paper presents experimental results on the low frequency electrical properties of an implementation made with carbon particles embedded on a polymer matrix forming a paste and printed on several textiles. The characterization of the relevant parameters as the sheet resistance and capacitance per unit area have been made in three different samples. A simple model allows to calculate the nominal resistance between two points of rectangular sheets of conductive layer. These values have been compared with measurements and the results show on one hand, the correctness of the model in the case that the sample has uniform electrical properties, and on the other hand, the possibility to detect changes in the uniformity of the electrical properties and thus the possibility to check the quality of the fabrication process of such conducting layers.

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