Effect of Protective Coating on the Performance of Wearable Antennas

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Abstract. Current smart clothing faces challenges due to discomfort provided by some technological components. A wireless body area network using inductively coupled fabric antennas is suggested as one of the solutions to overcome this. Different types of fabric substrates (denim, broadcloth, and jersey) and protective coating (acrylic resin, polyurethane, and silicone) were selected and engineered to optimize the antenna performance – in terms of mechanical and electrical properties. Experimental results show that protective coating affects almost every mechanical property very significantly. Resistance of the antenna was recorded lowest on the polyurethane-coated antennas and inductance was minimized on the broadcloth substrates. Recognizing a trade-off between electrical performance and comfort, this research looks at ways to optimize the overall usability.

Keywords: Smart clothing, Conductive printing, Protective coating, Fabric antenna, Inductive coupling, FAST.

1 Introduction

E-textiles refer to fabrics which can function as electronics or computers and physically behave as textiles. Both electrical properties (such as conductivity) and mechanical properties (such as flexibility) are very important in the creation of e-textiles [1]. The methods most commonly used to integrate conductivity into textiles are weaving, stitching, couching, knitting, and printing [2]. With a reduction in production cost over the other techniques, conductive printing contributes to the feasibility of mass production. Printability, which describes efficiency of conductive printing, is determined largely by whether conductive ink penetrates the substrate or remains on the surface, and is highly related to micro pores distributed on the fabric surface. Electrical conductivity of printed media is maximized when the printing remains on the surface of the fabric and does not penetrate into the fabric structure [3].

Protective coatings are necessary to ensure a long and effective working life of the printed media. Applied onto conventional printed circuit boards (PCBs), conformal coating refers to a protective non-conductive dielectric layer, whose thickness is up to 0.005 inches [4]. This coating protects PCBs from electrical arcing, environmental contamination, and physical damage. Typical conformal coatings are made by silicone, polyurethane, epoxy, or acrylic resin [4, 5]. According to the varying chemical

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and physical properties, they offer different degrees of protection, performance, and application. Protective coating is highly suggested for conductive prints on the fabric substrates as they may crack and peel off due to mechanical agitations during wearing or laundering. In order to improve the printing durability without sacrificing the flexibility of fabric substrates, flexible coating materials such as silicone or polyurethane are favorable. Polyurethane protective coating dramatically saves conductive prints from losing electrical conductivity after several laundering cycles [6]. It is observed that the protective layer holds the conductive ink together even if cracks and breaks occur in the ink layer [7].

This research aims to investigate the effect of different types of protective coating on the mechanical and electrical performance of wearable antenna printed on a variety of fabric substrates. Single jersey, broadcloth, and denim are selected to simulate common fabrics for everyday clothing. Three different protective coatings made of acrylic resin, polyurethane, and silicone are applied to the fabric surfaces before and after the conductive printing, which are intended to improve the printability of the silver ink and to prolong the life of conductive path, respectively. Results will be useful in determining which type of protective coating is effective to support conductive printing on specific fabric substrates, and will be of interest to professionals working with e-textiles for a variety of applications, such as healthcare, recreation, entertainment, and the military.

2 Wireless Body Area Network (BAN)

Wireless transmission is the transfer of electrical energy over a distance through electromagnetic waves. It is necessary to satisfy smart clothing users as they do not like wires all over their body which might get caught, broken, and tangled. Depending on the area the network can cover, wireless transmission network is categorized into Wide Area Network (WAN), Local Area Network (LAN), and Personal Area Network (PAN). Recently, prompted by the rapid growth in wearable technology and smart clothing field, the concept of wireless Body Area Network (BAN) has attracted much interest. Wireless communication in a few centimeter ranges can be realized between a set of compact intercommunicating devices either worn or implanted in the human body.

Inductive coupling is one of the methods used to obtain the connectivity between the devices. Two inductors are referred to as ‘inductively coupled’ when one wirelessly transfers electrical energy to the other by means of a shared magnetic field [8]. Typically, an inductively coupled system uses a coil antenna which can cover less than one meter distance to transfer data and power [9]. The coupling efficiency dramatically improves if resonance is involved. A LC circuit resonates at a specific frequency when the circuit impedance maximizes. Resonant frequency (F_0) of a parallel LC circuit (Figure 1) is known as follows.

$$F_0 = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

where, F_0 = resonant frequency, L = inductance, and C = capacitance

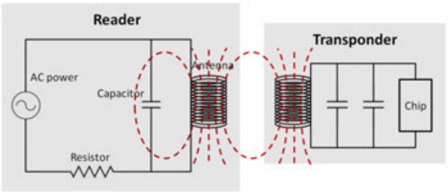

Fig. 1. A LC circuit inductively coupled

Inductive coupling is good to transfer electrical power and data signals wireless within a short distance. It is useful to transfer small packets of data without an integrated power supply. As a transponder is powered by the coupled magnetic field, it requires no battery and therefore, no interconnection to the power source [9]. Operating with low power consumption, inductive coupling is favored for continuous long-term communication. Also, inductive coupling is less sensitive to other radio frequency interferences [10] as it favors relatively lower frequency – typically, 13.56 MHz.

3 Fabric Antenna Production

Fabric antenna is produced by printing a spiral inductor on the various fabric substrates using silver conductive ink. Different types of protective coating are applied to secure the antenna area.

3.1 Material

Screen-printable silver ink is used as a conductive material. It contains 60% silver particle and its resistivity is reported as low as 2.5×10^{-7} Ω·cm. For the protective coating, silicone, polyurethane, and acrylic resin are selected as they are most common for conventional PCBs. Characteristics of the materials are specified in Table 1.

Table 1. Material Specifications

	Silver ink	Silicone	Polyurethane	Acrylic resin
Product	E-8205	422	4223	419B
Manufacturer	Sun Chemical®	MG Chemicals®	MG Chemicals®	MG Chemicals®
Solid content (%)	60	25	N/A	25
Viscosity (g/cm·sec)	25-30	0.11	1.8-2.4	2.2-2.4
Resistivity (Ω·cm)	2.5×10^{-7}	1.0×10^{14}	N/A	8.7×10^{15}

3.2 Fabric Substrate

Various fabric substrates are selected to print antennas such as denim, broadcloth, and jersey. Each is a fabric typically chosen for outer, inner, and underwear. Detailed information of the fabrics is given in Table 2. The print area is treated with the coating material identical to protective coating before the printing in order to improve the printability of the silver ink. The printed structure is shown in Figure 2.

Table 2. Fabric Substrate

Fabric Type	Structure	Fiber Contents (%)	Density (mg/cm^2)	Typical Applications
Denim	Twill weave	Cotton = 100	~42.8	Jackets, Pants
Broadcloth	Plain weave	Cotton = 100	~12.8	Dress shirts
Jersey	Sheer knit	Cotton = 100	~15.6	T-shirts

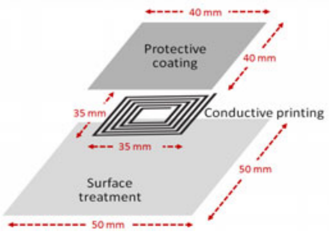

Fig. 2. Printed structure and dimensions

3.3 Antenna

Based on the literature [9, 11, 12], design for the antenna pattern (Figure 3) is created from a planar spiral inductor, which is 35mm × 35mm (Figure 2). It is manually printed on fabric substrates by screen printing using conductive silver ink. According to the ink manufacturer's recommendations, a screen frame is created with a polyester mesh of 230 tpi and the silver ink is cured at 90°C for 5-10 minutes after printing. This spiral inductor would serve as an antenna for wireless transmission within a few centimeter ranges at the frequency of 13.56 MHz.

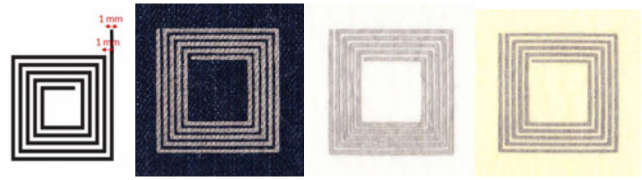

Fig. 3. Antenna pattern (*first*) printed on denim (*second*), broadcloth (*third*), and jersey (*last*)

4 Measurement

The fabric antennas are observed in terms of their mechanical properties before and after printing and coating to estimate the restrictions newly added by the antenna and protective layer. Electrical properties are tested by measuring resistance (R) and inductance (L) to evaluate the possibilities for a wireless transmission system. Mechanical performance is observed by measuring tensile, compression, bending, and air permeability characteristics. Fabric Assurance by Simple Testing (FAST) system is used to estimate extension and compression properties. Bending force and air permeability are accessed based on ASTM D4032 and ASTM D737, respectively. These measurements are listed in Table 3.

Table 3. Measurements for mechanical property

Property	Standard Method	Measures	Unit
Extension	FAST-3	Extension at three different loads	%
Compression	FAST-1	Compressible thickness	mm
Bending force	ASTM D4032	Force required to bend	N
Weight	N/A	Weight	mg/ cm^2
Air permeability	ASTM D737	Amount of air passing through	$cm^3/sec\cdot cm^2$

Fabric specimens are prepared as the standard testing methods instruct. All fabrics are washed prior to any treatment or measurement based on ASTM D4265. This is done to eliminate residues of mill finishing agents which might influence the experimental results. Then, they are conditioned in the standard atmosphere (21°C and 65% R.H.) at least 16 hours. As instructed, fabric specimens are prepared in dimension of 50mm × 200mm for extensibility test and 100mm × 100mm for the rest of the tests. Antenna area is 50mm × 50mm (Figure 2) for every specimen and located on the center of the specimens.

Electrical performance of the printed antenna is analyzed with resistance and inductance. Resistance (*R*) is a property to oppose current flow and resistors dissipate electrical energy. Inductance (*L*) is typified by the behavior of a coil of wire to resist the change of electric current through the coil and inductors have ability to temporarily store electrical energy in the form of magnetic field surrounding them. Resistance and inductance are estimated using a network analyzer, Agilent Technologies, E5071B ENA series. Two-way ANOVA (Analysis of Variance) judges the significant difference in mechanical and electrical performance between the antenna systems printed on the various fabric substrates with different protective coating layers. Tukey's post hoc test is chosen for further analysis. SPSS 19 was used for analysis.

5 Result and Discussion

5.1 Mechanical Performance

Mechanical properties of the untreated fabrics are described in Table 4. Extensibility is measured at three different load levels (5, 20, 100 gf/cm) in both warp and weft directions. Compression is observed by subtracting the thickness at the pressure of 100 gf/cm^2 from the thickness at 2 gf/cm^2, which may represent for the amount of compressible thickness on the fabric surface [13]. Bending force is obtained from the maximum pressure applied to bend the fabric. Air permeability measures the amount of air volume passing through the fabric specimen per unit area and unit time.

Table 4. Mechanical Properties of Untreated Fabrics

Coating Type		Unit	Denim	Broadcloth	Jersey
E5	(warp)	%	0.0 (± 0.0)	0.0 (± 0.0)	2.7 (±0.7)
	(weft)	%	0.0 (± 0.0)	0.1 (± 0.1)	5.0 (±0.3)
E20	(warp)	%	0.3 (± 0.1)	0.5 (± 0.3)	11.4 (±0.8)
	(weft)	%	0.1 (± 0.1)	1.5 (± 0.4)	19.5 (±0.4)
E100	(warp)	%	3.2 (± 0.4)	1.9 (± 0.4)	17.6 (±4.3)
	(weft)	%	1.2 (± 0.1)	6.6 (± 0.3)	21.5 (±0.0)*
T2		mm	1.311 (± 0.042)	0.557 (± 0.014)	0.903 (±0.016)
T100		mm	1.020 (± 0.016)	0.361 (±0.006)	0.656 (±0.006)
T2-T100		mm	0.291 (± 0.291)	0.195 (±0.013)	0.247 (±0.013)
Bending force		N	12.0 (± 1.2)	0.7 (±0.1)	0.4 (±0.0)
Weight		mg/cm^2	42.8 (± 0.8)	12.8 (± 0.2)	15.6 (±0.2)
Air permeability		cm^3/sec·cm^2	3.12 (± 0.07)	3.74 (±3.59)	57.57 (±1.19)

* 21.5% extension is the maximum measurement FAST system allows.

Tensile Property. All ANOVA models for the extension tests are very significant at 0.001 α-level. Significant difference by the fabric type is only observed with jersey fabrics (Table 5) which can be characterized by excellent extensibility as a knit fabric. The significance is primarily due to the significant difference between coated and non-coated fabrics (Table 6). Extensibility dramatically decreases after conductive printing and protective coating. As shown in Table 5, lower level extension (E5) does not have any significant difference among coating materials, while the difference between silicone and acrylic becomes apparent with higher level extension (E20, E100).

Table 5. Effect of Fabric Substrate on Antenna Extensibility (%)

Fabric Type	E5		E20		E100	
	(warp)	(weft)	(warp)	(weft)	(warp)	(weft)
Untreated Denim*	0.000^a	0.000^a	0.317^a	0.067^a	3.217^a	1.150^a
Untreated Broadcloth*	0.000^a	0.117^a	0.450^a	1.533^b	1.850^a	6.550^b
Untreated Jersey*	2.717^b	5.000^b	11.400^b	19.517^c	17.617^b	21.500^c
Denim	0.000^a	0.000^a	0.204^a	0.067^a	1.708^a	0.754^a
Broadcloth	0.008^a	0.050^a	0.208^a	0.663^b	1. 025^a	3.679^b
Jersey	0.992^b	1.668^b	5.367^b	9.263^c	10.713^b	18.563^c

(Superscript a, b, and c refer to the homogeneous subsets of the group)

* Untreated refers to bare fabrics where no antenna is printed and no coating is applied.

Table 6. Effect of Coating Material on Antenna Extensibility (%)

Coating Type	E5		E20		E100	
	(warp)	(weft)	(warp)	(weft)	(warp)	(weft)
Silicone	0.139^a	0.267^a	0.917^a	1.539^a	2.900^a	5.178^a
Polyurethane	0.122^a	0.283^a	1.200^{ab}	2.289^b	3.217^{ab}	7.444^b
Acrylic	0.167^a	0.061^a	1.533^b	2.246^b	4.250^b	8.306^c
Untreated*	0.906^b	1.706^b	4.056^c	7.039^c	7.5561^c	9.733^d

(Superscript a, b, c, and d refer to the homogeneous subsets of the group)

* Untreated refers to bare fabrics where no antenna is printed and no coating is applied.

The antenna area takes 50% of entire fabric specimen as the actual length fed in to the measurement is 100mm out of the 200mm. Most of extensibility must come from the bare fabric area, not from the antenna area. The antenna area is proven to contribute to the entire extensibility to some extent as extensibility is different depending on coating materials, but the level of extent could hardly be specified in this research. What can be verified from this research is that extensibility is reduced by approximately half to one third after the antenna system is applied (Table 5). Silicone provides the least extensibility and acrylic shows the most (Table 6).

Compression Property. ANOVA models are very significant at 0.001 α-level. As shown in Table 7, fabric thickness increased by ~0.3mm at 2 gf/cm^2 and ~0.2mm at 100 gf/cm^2 after the antenna system applied. Compression (T2-T100) of the fabric substrates becomes undistinguished as the antenna system is applied. Compression is known to be more related to the appearance or fabric hand than mechanical performance [13]. Silicone coating does not change fabric thickness significantly, while polyurethane and acrylic do. Compression (T2-T100) changes significantly after acrylic coating. It is only silicone that does not affect the thickness and compression of the fabric substrates (Table 8).

Table 7. Effect of Fabric Substrate on Compression of Fabric Antenna (mm)

Fabric Type	T2	T100	T2-T100
Untreated Broadcloth*	0.55650^a	0.36117^a	0.19533^a
Untreated Jersey*	0.90317^b	0.65600^b	0.24717^b
Untreated Denim*	1.31133^c	1.02033^c	0.29100^c
Broadcloth	0.88775^a	0.56917^a	0.31858^a
Jersey	1.22100^b	0.82271^b	0.39829^a
Denim	1.59321^c	1.17842^c	0.41479^a

(Superscript a, b, and c refer to the homogeneous subsets of the group)
* Untreated refers to bare fabrics where no antenna is printed and no coating is applied.

Table 8. Effect of Coating Material on Compression of Fabric Antenna (mm)

Coating Type	T2	T100	T2-T100
Untreated*	0.92367^a	0.67917^a	0.24450^a
Silicone	0.82744^a	0.72022^a	0.10722^a
Polyurethane	1.21311^b	0.95778^b	0.25533^a
Acrylic	1.97172^c	1.06989^c	0.90183^b

(Superscript a, b, and c refer to the homogeneous subsets of the group)
* Untreated refers to bare fabrics where no antenna is printed and no coating is applied.

Bending Property and Weight. Bending seems to be the property impaired most by the antenna system. The bending force is measured from the two-ply fabric specimens cut in 100mm × 100mm, respectively. The antenna area (50mm × 50mm) takes 25% of surface area. If 100% antenna area is tested, unrealistic numbers of bending force must have been reported.

The second column in Table 9 describes how dramatically the antenna system increases the bending force on every fabric substrate. Broadcloths and jerseys do not differ from each other, while denim fabrics have significantly huge bending force. Silicone has the least increase and polyurethane has the most (Table 10). This difference is very significant as much as the bending force becomes almost doubled for different coatings.

The third columns in Table 9 and Table 10 show the weight changes. Antenna system adds about 6-7 mg/cm^2 to fabric substrates. The change of weight depending on different coating materials is very significant. Silicone is the lightest (~7.1 mg/cm^2) and polyurethane is the heaviest (~10.8 mg/cm^2).

Air Permeability. Air permeability directly indicates thermal and moisture comfort of the fabric. Table 9 and Table 10 include the air permeability in its last columns. The antenna system diminishes air permeability by the one third of its original air permeability. This time, the antenna area covers about 65% of the fabric specimen area tested. Silicone coated antenna is the most permeable and polyurethane antenna is the least permeable.

Table 9. Effect of Fabric Substrate on Bending, Weight, and Air Permeability

Fabric Type	Bending force (N)	Weight (mg/cm^2)	Air permeability (cm^3/sec·cm^2)
Untreated Broadcloth*	0.717^a	12.800^a	33.7400^b
Untreated Jersey*	0.400^a	15.633^b	57.5733^a
Untreated Denim*	12.033^b	42.783^c	3.1250^c
Broadcloth	21.950^a	18.146^a	22.4917^b
Jersey	25.592^a	22.337^b	33.7979^a
Denim	113.163^b	50.104^c	2.3188^c

(Superscript a, b, and c refer to the homogeneous subsets of the group)

* Untreated refers to bare fabrics where no antenna is printed and no coating is applied.

Table 10. Effect of Coating Material on Bending, Weight, and Air Permeability

Coating Type	Bending force (N)	Weight (mg/cm^2)	Air permeability (cm^3/sec·cm^2)
Untreated*	4.383^a	23.739^a	31.4794^a
Silicone	33.672^b	30.850^b	17.9783^b
Acrylic	60.289^c	31.678^c	16.0544^c
Polyurethane	115.928^d	34.517^d	12.6322^d

(Superscript a, b, c, and d refer to the homogeneous subsets of the group)

* Untreated refers to bare fabrics where no antenna is printed and no coating is applied.

5.2 Electrical Performance

Electrical performance of printed antenna is evaluated by measuring resistance and inductance. Low resistance and high inductance are observed when the conductive ink is printed on the fabric surface consistently and reliably. Fabric substrates have significant effects on antenna resistance, while coating materials influence antenna inductance.

Resistance. Polyurethane-coated antennas exhibit significantly low resistance (Table 11). The solvent used in silicone and acrylic, which is xylene or acetone, is considered to penetrate the silver ink layer impairing its conductivity. Polyurethane which does not contain solvent component could secure the silver ink layer successfully compared to silicone and acrylic.

Table 11. Effect of Coating Material on Resistance and Inductance

Coating Type	Resistance (Ω)	Inductance (nH)
Polyurethane	52.06^a	940.07^a
Acrylic	137.85^b	785.84^a
Silicone	158.78^b	764.63^a

(Superscript a and b refer to the homogeneous subsets of the group)

Inductance. Significantly superior inductance appears on denim and jersey antennas (Table 12). Due to its light weight and low fabric density, broadcloth does not have enough capacity to hold the large volume of coating materials applied by surface treatment before printing, and this might result in low antenna quality.

Table 12. Effect of Fabric Substrate on Resistance and Inductance

Fabric Type	Resistance (Ω)	Inductance (nH)
Denim	100.23^a	905.31^a
Jersey	114.94^a	922.46^a
Broadcloth	122.42^a	624.37^b

(Superscript a and b refer to the homogeneous subsets of the group)

6 Conclusion

The experimental results show that the selection of fabric substrates and coating materials needs to be considered after evaluating every mechanical and electrical performance. For example, silicone-coated antennas are extended the least which might be a weak point from comfort side, but regarded also as a strong point from antenna protection point of view. This research does not extend its scope to durability of the antenna against the mechanical deformation. It has been reported from previous research [6, 7] that protective coating could prolong the lifetime of conductive prints successfully.

Silicone-coated antennas are reported to be the most flexible, while polyurethane-coated ones are most rigid. However, polyurethane-coated antennas exhibit significantly low resistance, which is beneficial to establish powerful wireless transmission. Acrylic is measured better than polyurethane in bending and air permeability, but in fact, acrylic does not show any recovery from the deformation, while polyurethane or silicone does. Acrylic antenna results in permanent deformation such as cracks on its surface after the mechanical deformations, which must disqualify it as proper protective materials.

As another variable affecting the mechanical property of the fabric antenna, the percentages of antenna area over the entire fabric specimen will be of interest for future research. Further steps of this research will include the measurement of actual wireless transmission between two fabric antennas when resonance is involved.

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