ABSTRACT

SUH, MINYOUNG. Development of Wireless Transmission between Inductively Coupled Layers in Smart Clothing. (Under the direction of William Oxenham and Kate Carroll.)

The goal of this dissertation was to improve the overall usability of smart clothing products by investigating the feasibility of wireless transmission to link multiple fabric layers in smart clothing. Antennas were printed on the fabric substrates using silver inks. To assure the printability and protection, necessary printing structure was configured, which were surface coating, conductive printing, and protective coating.

Two research phases were employed to achieve this goal. The first phase aimed to investigate the effect of fabric substrates and coating materials on the electrical and mechanical performance of printed antennas. The fabric substrates and coating materials were selected from woven and knit fabrics for everyday wear (denim, broadcloth, and single jersey) and from conventional conformal coating materials (acrylic, polyurethane, and silicone), respectively. Fabric substrates could be selected depending on different end-use applications as they were not affecting the antenna performance much. Silicone coating was suggested to support the antenna performance with mechanical performance of fabrics impaired the least.

For the second research phase, physical conditions of the fabric antenna were explored to find out their influence on transmission performance. The physical conditions included distance, dislocation, stretching, and bending. Wireless transmission between the fabric antennas was influenced much by the conditions in which they were situated. Based on the

regression models, the limits of physical conditions that enable proper wireless transmission were estimated up to ~2 cm for distance and dislocation and 0.3 K (a circle with ~3 cm radius) for bending. These numbers imply the inductively coupled antennas have much potential for smart clothing uses.

Development of Wireless Transmission between Inductively Coupled Layers
in Smart Clothing

by
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DEDICATION

to

Sun-Ock Lee, Ph.D.

For lifetime mentoring to be a great scholar and a wise woman

as well as for being Mother

in the year of her sixtieth birthday

BIOGRAPHY

Minyoung Suh was born on September 16th, 1980 in Seoul, Korea. She received two Bachelor of Science degrees in Clothing & Textiles and Human Environment & Design on February, 2003 from Yonsei University, Seoul, Korea. She worked for Inthef Company (an apparel producer), as a textile designer. She joined North Carolina State University, NC to start master's study in Textile Management and Technology on August, 2006, and continued to doctoral program in Textile Technology Management from August, 2008. She expects to graduate on May, 2011.

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Finally, the author wishes to express sincere appreciation and love to her parents for their constant support and encouragement during the entire study. Gratitude extends to her sister, brother-in-law, brother, and a brand new-born nephew, Dominic Kim. As the emotional prop throughout the life, her great grandmother deserves the most and best appreciation.

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CHAPTER I. INTRODUCTION

A review of the literature on smart clothing raises the issue of some impracticalities in the current smart clothing system. Even though they are capable of multiple types of smart functions, current smart clothing systems are not always wearable. The problem of wearability begins with the definition of the word ‘wearable’. Initiated from the concept of a wearable computer, a wearable system was understood as the use of a piece of clothing to support technological devices on a body, which is much different from the concept of wearability from a typical clothing perspective. No matter how effectively it makes full use of very high level of technological functions, smart clothing which looks awkward or feels uncomfortable will not be marketable. Previous researchers (Gniotek & Krucinska, 2004; Linz, Kallmayer, Aschenbrenner, & Reichl, 2005; Mattila & Textile Institute, 2006; Meoli & May-Plumlee, 2002; Slade, et al., 2002) have pointed out the impracticality of smart clothing systems because of the lack of wearability.

This research was devoted to improve usability of smart clothing in system approach. Considering psychological, physical and functional aspects, the objective was set to validate the feasibility of wireless link between multiple layers of smart clothing. Replacing the wires crisscrossing around the body, the biggest merit of wireless system is the improved appearance which appeals strongly to smart clothing users. Moreover, wireless system would make it possible to link different layers, which was previously unattainable with wires. This enables to incorporate diverse and separate tasks that can be achieved on inner layer and outer layer of smart clothing and to establish multi-layered smart clothing system.

Disappearing wired interfaces, inductively coupled antennas were selected to obtain wireless communication. As part of a Body Area Network (BAN), the inductive coupling is characterized by short range communication and low power consumption, which is appropriate for wearable applications.

Research was designed to cover both the effect of technology on clothing comfort and effect of wear situation of clothing on technological performance. Inductor antennas integrated into fabric substrate were evaluated in terms of usability (i.e. comfort and electrical performance). Physical conditions in which the fabric antennas would be situated were investigated in order to validate the feasibility of inductive coupling for wearable applications.

Two research phases were employed to achieve this goal. The first phase aimed to investigate the effect of fabric substrates and coating materials on the electrical and mechanical performance of printed antennas. Inductors were printed on the fabric substrates using silver inks. The fabric substrates were selected from woven and knit fabrics for everyday wear which are commercially available in the market. Using the conformal coating materials for conventional printed circuit boards (PCBs), two coating layers were added on the fabric surface. These coating layers were required to increase the printability of silver ink and to prolong the life of conductive path, respectively. For the second research phase, physical conditions of the inductively coupled fabric layers were explored to find out how much influence they have on transmission performance. The physical conditions included distance (interval between two fabric antennas), dislocation (relative location of two fabric antennas), stretching (tensile deformation of fabric antennas), and bending (curving deformation of fabric antennas).

CHAPTER II. LITERATURE REVIEW

2.1. Smart Clothing

2.1.1. Definitions

Smart clothing is a name given to garments which “change” in response to stimulants. Primarily, this is a garment which can provide interactions for users by sensing signals, processing information, and actuating responses. Smart clothing can provide non-traditional garment functions, such as health monitoring, as well as traditional garment functions, such as protecting the body (McCann & Bryson, 2009). Other terminologies, such as interactive clothing, intelligent clothing, and smart garments, have been used interchangeably to indicate this type of garment.

Electro-textiles, known as e-textiles, refer to fabrics which can function as electronics or computers and physically behave as textiles. E-textiles are located in the potential area of intersection between textiles, electrical engineering, and information science (Gniotek & Krucinska, 2004; Muth, et al., 2002). Multidisciplinary environment for E-textiles is diagramed in Figure 2- 1. Depending upon the different approaches adopted, E-textiles are also called smart textiles, intelligent textiles, wearable electronics, and wearable computers.

A wearable computer is a computing device assembled in a way which allows it to be carried on the body (McCann & Bryson, 2009). The concept was initiated from the computer being accessible, wherever the user goes. While a wearable computer has both input and output systems for full computation, a wearable electronic is constructed with a set of tasks to fulfill one or more needs (McCann & Bryson, 2009). Accordingly, wearable electronics are simpler than full-scale wearable computers. A wearable electronic is best thought of a mobile device which is integrated into what can be worn on the body. As such it should not detract from the tactivisual properties of the garment.

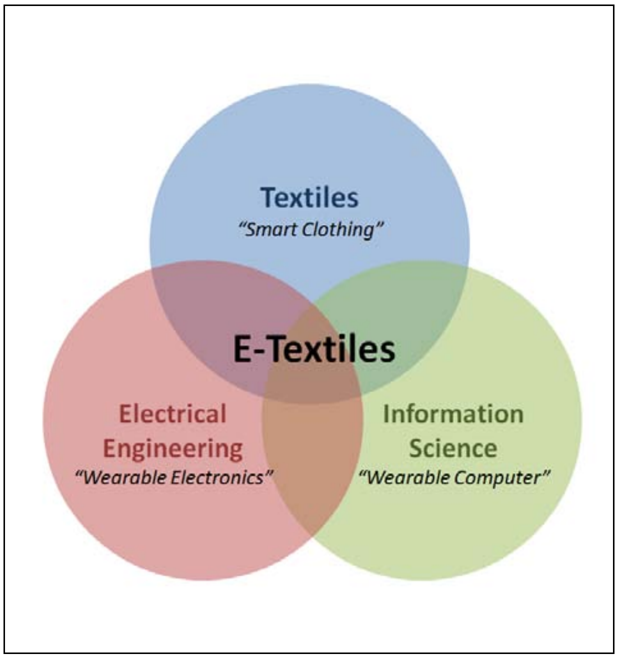


Figure 2- 1. Multidisciplinary Environment for E-textiles
(Gniotek & Krucinska, 2004)

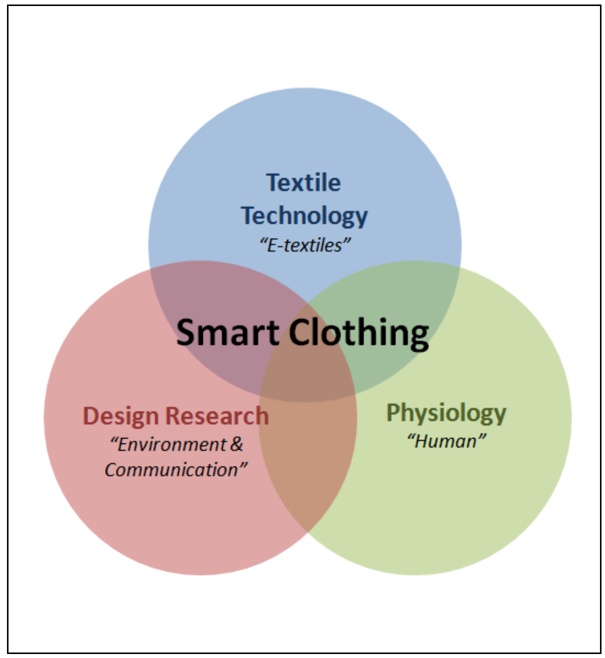


Figure 2- 2. Multidisciplinary Environment for Smart Clothing
(Mattila & Textile Institute, 2006)

Initiated from wearable computers, current smart clothing systems are not very practical to wear (Gniotek & Krucinska, 2004; Linz, et al., 2005; Mattila & Textile Institute, 2006; Meoli & May-Plumlee, 2002; Post, Orth, Russo, & Gershenfeld, 2000; Slade, et al., 2002). Smart clothing has been developed with cables crisscrossing around the body, and batteries or hard electronics sticking out from the surface. With these constraints, wearers have a lack of variety in their appearance limited to the fixed look that is dictated by the technology, not the garment design. In order to overcome the impracticality of the current smart clothing systems, it has been suggested to look at smart clothing as an object of interdisciplinary research from three research disciplines; textile technology, physiology, and design (Mattila & Textile Institute, 2006). Multidisciplinary scholarship surrounding smart clothing is schematized in Figure 2- 2. Each field represents the material, the human, and their interaction.

2.1.2. Historical Development

Mainly developed for military use in the United States and European countries in the 1990s, smart clothing has prospered in the field of medicine and sportswear. Based on the historical innovations in research and development (R&D) and in the market, four developmental phases were distinguished and characterized; (1) portable technology – 1980s to 1997, (2) multidisciplinary collaboration – 1998 to 2001, (3) market opportunity – 2002 to 2005, and (4) popularization and expansion – 2006 to current (Ariyatum, Holland, Harrison, & Kazi, 2005; McCann & Bryson, 2009). Significant advances in each phase are listed chronologically in Table 2- 1.

Table 2- 1. History of Wearable Systems Development

	1980 – – – – – – – – – – 1997 **1ST STAGE**	1998 – – – – – – – – – – – 2001 **2ND STAGE**	2002 – – – – – – – – – – 2005 **3RD STAGE**	2006 – – – – – – – – – **4TH STAGE**
R&D	▪ Steve Mann, Cyberman project ▪ MIT Media Lab., Lizzy project ▪ Sensatex, US military project ▪ Philips Research, Vision of Future project ▪ Bristol Univ., Sensory Fabric project	▪ Alexandra Fede with Du Pont and Mitsubishi ▪ SoftSwitch, Softswitch technology ▪ Tampere Univ., Intelligent textiles survey ▪ Georgia Tech., Wearable Motherboard ▪ Eleksen, Fabric keyboard	▪ Infineon Technologies, MP3 player jacket ▪ Tokyo Univ., Transparent Clothes project ▪ Information Society Technologies, Wealthy project	▪ Konarka Technologies and Textronics, Wearable power generator ▪ Idaho National Laboratory, Solar energy fabric
E-textile Market		▪ SoftSwitch, Fabric Keyboard	▪ Eleksen, “Logitech Keycase”	▪ Fibretronic, “ConnectedWear”
Smart Clothing Market		▪ Philips & Levis, “ICD+ Jacket”	▪ Sensatex, “Smartshirt” ▪ North Face, Self-heating Jacket ▪ Vivometrics, “LifeShirt” ▪ Burton, “MD Jacket” ▪ Burton, “Amp Jacket” ▪ GapKid, FM radio shirt ▪ Adidas, Self-adapting shoes	▪ Levis, iPod jean ▪ Zegna, Bluetooth iJacket ▪ Zegna, Solar Jacket ▪ Metallica, “Metallica M4 Jacket” ▪ Oakley, Solar beach tote

The early concept of smart clothing was introduced with the idea of the wearable computer. The focus of research projects in the first developmental phase was to produce computing hardware in a portable form merely to exhibit the advanced technologies. The outcomes were portable rather than wearable because the clothing was used only as a platform to support technological devices.

The second developmental phase was characterized by a number of collaborative projects between electronic and fashion fields. The fashion and textile sectors started to challenge wearable systems. The first commercial wearable system was introduced in 2000 after the collaboration between Phillips Electronics™ and Levi Strauss™ (Figure 2- 3). It was a jacket with special pockets for mobile devices (McCann & Bryson, 2009; Philips Design, 2000). The applications became more wearable, but still technical feasibility was the core issue because technology stayed underdeveloped.

Figure 2- 3. ICD+ Jacket by Phillips Electronics™ and Levi Strauss™

In the third phase, product marketability attracted more interest as many research teams realized the requirements of further input from fashion industry and user analysis. The major approach had shifted to a user-centered perspective, while other researchers kept up their technical studies. Technologies to miniaturize electronics attracted much interest of the researchers and therefore, the miniaturization speeded up (Peercy, 2000). The semiconductors have scaled down to the micrometer levels. Micro-electronics with low power consumption provided the market with the opportunities to create more comfort and normal-looking smart clothing systems (Ariyatum & Holland, 2003).

Thanks to the progress achieved in previous phases, wearable systems for entertainment became popularized in the market during the fourth phase. A few high fashion brands jumped into smart clothing development in this period. For example, Zegna Sport™ launched a series of jackets equipped with digital media players and solar power systems (Figure 2- 4). The growth in the entertainment segment brought a ripple effect in other segments such as healthcare and energy. Functionality of smart clothing was not limited to managing personal electronics, but expanded to monitor the wearer’s condition or to create renewable and wearable energy sources, such as solar or kinetic energy (McCann & Bryson, 2009; Seymour, 2008).

Smart clothing or wearable electronics have become more and more feasible with the micro-sized electronic devices. Based on scaling of electronic devices to smaller and smaller sizes, micro-electronics have evolved into nano-electronics. Currently, the size of integrated circuit is only ~45 nm long and wide, and only 1-2 nm thick (Cerofolini, 2009). Microelectronics requires reliable and fairly portable power source supplying suitable voltages and currents from practically unlimited power source. In order to sustain long battery life, microelectronics need to be operated at the lowest possible supply voltage. Low power design has rapidly evolved to the mainstream of microelectronics. The most urgent demands for low power electronics originated from the stringent requirements for small size, light weight, long operating life, utility and reliability of the equipments operated with batteries

Figure 2- 4. iJacket by Zegna Sport™

The market for smart fabric and interactive textiles has been rapidly growing with the average growth rate of 20% for last decade. According to the British Chamber of Commerce, market for smart fabric and interactive textiles was about $ 299 million in 2009 (Cluster of EC Co-Financed Projects on Smart Fabric Interactive Textile, 2010). The sector for general consumers took the highest portion of the market, followed by safety professionals (Figure 2-5). While different researchers label each segment differently (Ariyatum & Holland, 2003; McCann & Bryson, 2009; S. Park & Jayaraman, 2003), the current market segments for smart clothing can be summarized into general public, the disabled or elderly, healthcare recipients, athletics, and working professional (Suh, Carroll, & Cassill, 2010). The market growth rate varies dramatically depending on the segment and high growth is expected for the general public and for healthcare segments.

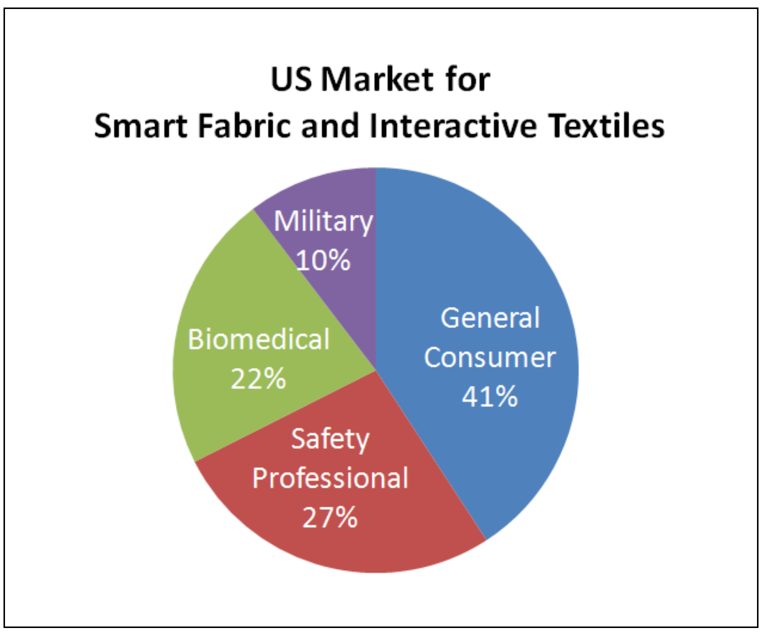


Figure 2- 5. Smart Fabric & Interactive Textiles Market
(Cluster of EC Co-Financed Projects on Smart Fabric Interactive Textile, 2010)

2.1.3. Degree of Technology Integration

Aesthetically pleasing design is an integral part of the success in fashion and apparel industry because clothing is a product highly appealing to the aesthetic preference of the user. During the development of functional clothing, the fashion industry cannot be expected to adapt itself to technology and vice versa. Consumers wear functional clothing for their special needs, but they do not want to be limited in other needs such as comfort and aesthetics (Lamb & Kallal, 1992). Before starting to design smart clothing, a product developer has to set a balance between fashion (i.e. aesthetics or style) and function (i.e. technical performance).

The balance is closely related to the degree of technology integration (Table 2- 2). The implant seems the best way to fully integrate technology into the human body (Gale & Kaur, 2004; Seymour, 2008), but there are many problems with biocompatibility. Also, due to human rights and privacy issues, implantable technology has many challenges. A wearable type of technology that would be less intrusive is classified into three groups; integration, embedment, and contents. Integration within a garment is preferred for aesthetic purposes as the technology is camouflaged within an intrinsic part of the garment. Embedment or contents can realize more sophisticated technological functions (Gale & Kaur, 2004). While the embedment level is for permanent attachment of smaller devices, the contents level is for temporary carrying of small devices. Hand-held devices are what the contemporaries are already enjoying in everyday life with many portable devices such as mobile phones.

Table 2- 2. Degree of Technology Integration (Gale & Kaur, 2004; Seymour, 2008)

Degree	Type		Description
High	Implanted		Such as implants or tattoos
↑	Wearable	Integration	Technology is integrated into the fabric as an intrinsic part
		(e.g. fabric itself equivalent to the electrical circuitry)	
		Embedment	Technology is physically attached or embedded into clothing or textile substrates
		(e.g. sandwiching devices between fabric layers)	
		Contents	Clothing is the container for the technology
↓		(e.g. pocketing devices within the garment)	
Low	Handheld		Such as mobile devices

Until every aspect of the technical component is made out of a dedicated textile material without any functional limitation, there exists a challenge for technology to be an intrinsic part of the clothing system. Accordingly, technology at the level of embedment or contents has prevailed so far in which micro-electronics are physically adhering to the clothing. Connection technology has been an important issue through which the power supply and data exchange is implemented (McCann & Bryson, 2009) as the electronics will not operate if not properly connected.

For the electronics miniaturized in the form and size of a button, for example, special sewing techniques are required at the joint points. Sewn connection is preferable to be used inconspicuously in the clothing, but with the possibility of the stitches coming loose, the stability of the connection can be uncertain (Locher, Kirstein, & Troster, 2004). Sewing may be replaced by soldering or welding (Dhawan, Ghosh, Muth, & Seyam, 2008; Lehn, Neely, Schoonover, Martin, & Jones, 2004) and bonding (Locher & Troster, 2007a; Post, et al., 2000). A plugged connection is desirable for technology at the contents level due to easy attachment and removal. Classical snap fastener is durable, but frequent connection and disconnection may weaken the adherence of snap itself (Lehn, et al., 2004). As an alternative, wireless connection has been also investigated recently (Lee, Yoo, & Yoo, 2009; J. Yoo, Yan, Lee, Kim, & Yoo, 2010).

Table 2- 3. Level of Expressiveness and Functionality (Seymour, 2008)

Level		Description	Application
Expressiveness ↑	1	The fashionable wearables are implements for personal expression and the functionality is less important.	High Fashion
|	2	The fashionable wearables have a defined function and some need to be stylish.	Sportswear
↓ Functionality	3	The functionality is the focal point. The necessity for personal expression is limited by strict pre-defined functionalities and restrictions.	Workwear

The degree of technology integration is highly dependent on the demands for expressiveness and functionality of smart clothing. Expressiveness is based on the socio-cultural and psychological aspects of the clothing, while functionality is oriented from the practical assistive performance which embedded technologies can provide to the wearers. Seymour (Seymour, 2008) defined three levels of expressiveness and functionality for smart clothing (Table 2- 3). Level one indicates the highest expressiveness and level three represents the highest functionality. They have different end-use applications.

2.1.4. Usability of Smart Clothing

Usability of smart clothing can be investigated from user analysis. Traditionally, functional design has been characterized by user-centered design process (Suh, et al., 2010). Identification of user requirements must provide important design considerations which have to be included in smart clothing. General requirements are to look good, not to bother users, to function properly, and to be easily maintained. Based on the user experience, the multidimensional usability of smart clothing can been categorized into four dimensions; psychological, physical, functional, and managerial. Figure 2- 6 summarizes the dimensions of usability from previous researches (Chae, Cho, Kim, & Han, 2009; Chae, Hong, Cho, & Han, 2007; Dunne & Smyth, 2005; Knight & Baber, 2005; McCann, Hurford, & Martin, 2005; S. Park & Jayaraman, 2003).

Figure 2- 6. Usability of Smart Clothing

Psychological considerations relate to appearance and safety of smart clothing (Chae, et al., 2009; Chae, et al., 2007; Knight & Baber, 2005; McCann, et al., 2005). The appearance is the emotional concern of a user about how they might look in smart clothing. Elements of design, such as color, form, texture, and pattern, play important roles in creating a pleasing appearance, while cultural influence may change the appropriateness of appearance (McCann, et al., 2005). Safety refers to worries or anxieties about how they might feel relaxed and secure in smart clothing. The worries are mostly about the system whether the clothing is functioning reliably as intended.

Physical attributes have been of most interest in usability of smart clothing for the past decade. Directly or indirectly, smart clothing is not supposed to feel strange, cause discomfort, restrict the movement, and damage the body. This can be regarded as a significant requirement of smart textiles as a garment. Weight and bulk distribution, mobility, sizing and fit, thermal and moisture management are the major issues (Dunne & Smyth, 2005). These issues are based on the understanding of human physiology.

Functional attributes describes how well the technological device plays its role in smart clothing, for example, how well it is monitoring vital signs or entertaining the users. This is the function of smart clothing as an electronic device. Previously, the successful functionality was the core developmental issue for smart clothing with primitive wearable technologies. The latest developmental approach focuses more on optimization of functionality in order to improve overall usability. Functionality can be judged from accessibility, manufacturability, data rates, fault tolerance, battery life, and so forth (S. Park & Jayaraman, 2003).

Managerial requirements must be considered in smart clothing. Ease of maintenance can be described from a garment perspective and an electronic perspective. The former is whether the smart clothing is washable, durable, and dimensionally-stable for long term use (Chae, et al., 2009; Dunne & Smyth, 2005; S. Park & Jayaraman, 2003). Cost reduction to produce disposable smart clothing can be an alternative. The latter includes a rechargeable battery and upgradable software (S. Park & Jayaraman, 2003).

The challenge is that the functional usability often conflicts with other usability aspects since functional forms do not necessarily emerge as a consequence of psychological and physiological pleasure. Rather, a design to satisfy functional demands inherently produces troubles with the aesthetic or comfort requirements (Bryson, 2007). For example, functional preference for extended battery life must result in huge and awkward-looking batteries additionally attached. Nowadays, it is attracting more attention to compromise functional requirements in order to optimize overall usability (Chae, et al., 2007).

2.2. Conductive Fabric

A conductive path is the most basic component of the circuitry. It should be included in fabrics as an intrinsic part because users of smart clothing do not like wires or cables which would get caught, broken, and tangled. A fundamental for a successful e-textile is to create reliable conductive tracks or wiring structures that do not hinder the user with mechanical characteristics (Locher & Troster, 2007b).

2.2.1. Creation of Conductive Path

Typical conductive materials are metals. Copper, stainless steel, and silver are most common. Copper is the most desirable conductor in terms of cost and conductivity, but it is notorious for corrosion and discoloration by acid and moisture (B. Park, Kim, Jeong, Moon, & Kim, 2007). Limited to low conductivity, stainless steel has an advantage in that it exhibits superior stability resistive to acid and moisture. Silver can be handled with ease since it is more resistant to oxidization compared to copper, while it has fairly low specific resistance, similar to copper. Hence silver is used widely in smart clothing applications (Laerhoven, Villar, & Gellersen, 2003; Locher & Troster, 2007b; Ono, Okada, Kondo, & Kurosawa, 2006; Rattfält, Lindén, Hult, Berglin, & Ask, 2007a). The conductive materials are combined with non-conductive components, which are polymers, into wearable systems. As the system takes a bigger portion of conductive materials, it loses the typical textile properties such as flexibility or drapability as it becomes more conductive.

The methods to integrate metals into textiles are weaving (Figure 2- 7), stitching (Figure 2- 8), couching (Figure 2- 9), knitting (Figure 2- 10), and printing (Figure 2- 11). Weaving conductive yarns as a warp or a weft (Chiou, Chiu, Liu, & Wu, 1999; Cottet, Grzyb, Kirstein, & Troster, 2003; Dhawan, Seyam, Ghosh, & Muth, 2004; Muth, et al., 2002) is one of the simplest ways. Empirically, plain weave is found desirable because its construction represents the most stable structure where no lateral yarn movement is possible. Stitching (Linz, et al., 2005; Linz, Kallmayer, Aschenbrenner, & Reichl, 2006) or couching (Post, et al., 2000; Tao & Textile Institute, 2001) a conductive thread is beneficial in that a conductive path can go in any direction crossing over seams in apparel composition. Embroidery, previously understood only for decorative purposes, creates potential for electronic embroidery or e-broidery. A knitted structure consists of interconnected loops which results in high stretch fabrics (Rattfält, et al., 2007a; Rattfält, Lindén, Hult, Berglin, & Ask, 2007b). Knitting usually requires more flexible yarns than any other structure because the yarn is highly curved to form a loop. Printing or plating conductive inks directly on the fabric surface is the most common (Cho, Moon, Jeong, & Cho, 2005; Cho, Moon, Sung, Jeong, & Cho, 2007; Karaguzel, et al., 2008, 2009; Locher & Troster, 2007b). Printing often causes stability issues for long term conductivity because the printed conductive layer is brittle. \]

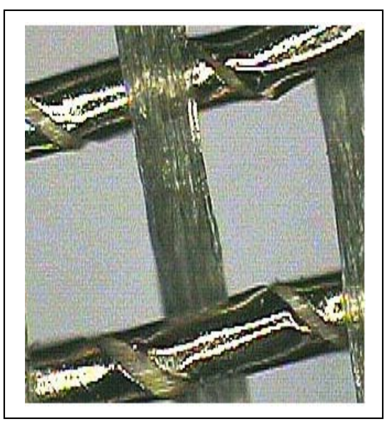


Figure 2- 7. Weaving Conductive Path
(Post & Orth, 1997)

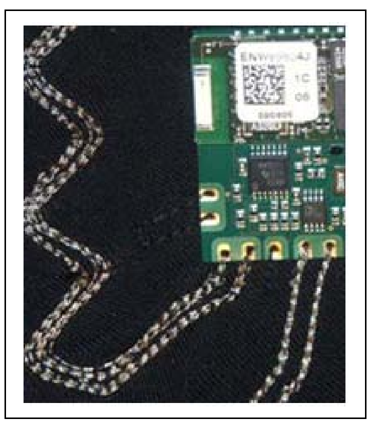


Figure 2- 8. Stitching Conductive Path
(Linz, et al., 2006)

Figure 2- 9. Couching Conductive Path
(Post, et al., 2000)

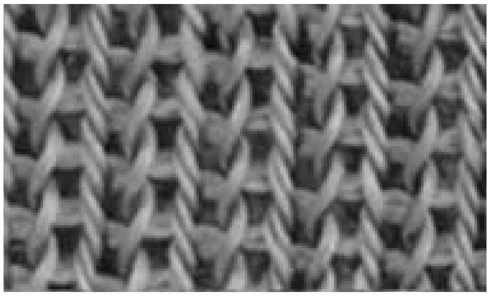


Figure 2- 10. Knitting Conductive Path
(Rattfält, et al., 2007a)

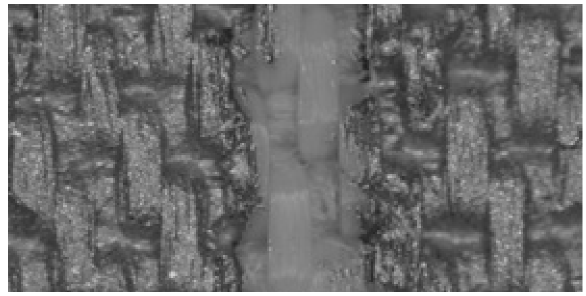


Figure 2- 11. Printing Conductive Path
(Locher & Troster, 2007b)

2.2.2. Conductive Printing

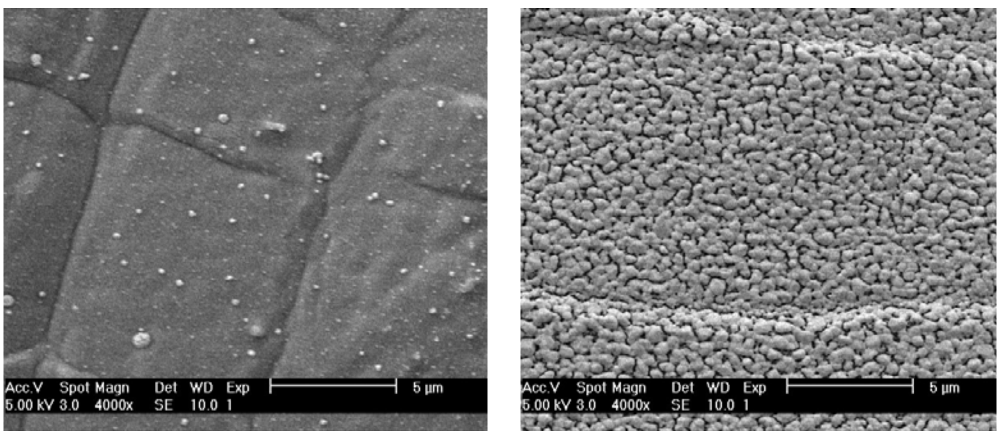
Conductive printing contributes the ease of mass production with a reduction in production cost over the traditional production techniques (Meoli & May-Plumlee, 2002; Perelaer, de Gans, & Schubert, 2006). It is often challenged in terms of durability issues due to cracking or peeling occurring on the ink layer. In order to stretch and bend without cracking or peeling, it is suggested that the flexibility of conductive ink must equal or exceed that of the fabric substrate (Karaguzel, et al., 2009).

Printability is decided largely by whether conductive ink penetrates the substrate or remains on the surface, which is highly related to micro pores distributed on the fabric surface. According to Karaguzel et al. (2008) the substrate with pores in a larger size experienced a thinner ink layer on the surface, which meant that a large amount of conductive ink penetrated into the substrate. In contrast, the smaller pore size did not allow conductive ink to go through the substrate and showed the lowest resistance on the printed track (Karaguzel, et al., 2008). Electrical conductivity of printed media is optimized when the printing takes place mostly on the surface.

Other factors are also involved in printability such as ink viscosity, mesh count, and squeegee hardness. Higher viscosity can prevent ink from spreading over the fabric surface and create thicker ink layer (Karaguzel, et al., 2008). Lower mesh count is beneficial to deposit more ink, while a higher mesh count screen can produce an image of higher resolution. A softer squeegee or repeated printing leaves a thicker ink deposit (Locher & Troster, 2007b). The thick ink layer is beneficial to electrical performance but disadvantageous to mechanical performance. The repetition is also obstructive to the fineness of printed image, especially on the edges where a weak concentration of ink is observed (Dearden, et al., 2005; Perelaer, et al., 2006).

Silver conductive ink is prepared by dissolving a synthesized silver into a non-polar organic solvent (Dearden, et al., 2005). Due to the evaporation of the solvent, significant loss of mass occurs after printing. The curing process is conducted by heating the printed surface in which radiation, conduction, and convection are involved. Typically, high temperature around 200°C and long heating time about an hour are required (Perelaer, et al., 2006). As shown in Figure 2- 12, the homogeneous surface of printed silver traces changes into the locally crystallized structure after the heat treatment (Dearden, et al., 2005; Perelaer, et al., 2006). This is due to rapid evaporation of solvent which limits the movement of silver particles, and therefore results in localized crystal growth (Dearden, et al., 2005).

Curing temperature and time have significant effects on the performance of printed media. The electrical resistance of conductive traces is measured highest under the lower curing temperature (Dearden, et al., 2005; Locher & Troster, 2007b; B. Park, et al., 2007). According to Dearden et al. (2005) and Perelaer et al. (2006) the rate of mass loss in silver conductive ink becomes rapid as the curing temperature increases above 150°C and the resistivity of printed media stabilizes at the low level around this curing temperature, as well. The resistivity largely decreases after a certain period of curing time, but extended time above that point does not improve the conductivity (Perelaer, et al., 2006).



(a) before curing (b) after curing

Figure 2- 12. Microstructure of Silver Ink (Perelaer, et al., 2006)

2.2.3. Protective Coating

Protective coatings are necessary to ensure a long and effective working life of conductive components. 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 (Khandpur, 2006). Some coatings are hard, while others have a slightly rubbery texture. The coating protects PCBs from electrical arcing, environmental contamination, and physical damage. In the past, this coating was only applied to military and life/medical products for quality assurance. In recent years, however, it is becoming more common as circuitry and electronic components continue to shrink in size and dimension as arcing occurs when voltage jumps from one conductive trace to another in close proximity.

Typical conformal coatings are made by silicone, polyurethane, epoxy, or acrylic resin and offer a clearly visible shine to the material when coated. They offer different degree of protection, performance, and application as the chemical and physical properties of the materials differ from each other. The basic characteristics of these coating materials are described in Table 2- 4. Flexibility of silicone coating allows for much thicker layer build up than comparable acrylic or urethane coating. Typical application methods are spraying, brushing, or dipping (Khandpur, 2006; Smith, 2008).

Protective coating is highly suggested for conductive prints on fabric substrates as they 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. According to Cho et al. (2007), polyurethane protective coating dramatically saves conductive prints from losing electrical conductivity after several laundering cycles. It is observed that the protective layer holds the conductive ink together even if cracks and breaks occur in the ink layer (Karaguzel, et al., 2009). The thermoplastic urethane layer works as a good mechanical barrier, but, depending on the fabric substrates, it can be lost after repeated washing (Karaguzel, et al., 2009).

Table 2- 4. Conformal Coating Materials (Khandpur, 2006; Smith, 2008)

	Silicone	Polyurethane	Epoxy	Acrylic Resin
Surface resistivity (Ω/cm)	~10^{13}	~10^{14}	~10^{13}	~10^{14}
Heat resistance (°C)	200	125	125	125
Moisture resistance	High	High	High	High
Acid resistance	Low	High	High	Moderate
Flexibility	Flexible	Hard	Hard	Hard
Durability	Moderate	High	High	High

2.3. Physical Properties and Physiological Comfort

Comfort takes one of the highest priorities in the functional value of clothing (Lamb & Kallal, 1992; Rosenblad-Wallin, 1985). Comfort of clothing is a complex subject that is very difficult to define as clothing is structured from several pieces of planar fabrics sewn or fused together. The biomechanical performance of clothing is believed to be very much dependent on mechanical and surface properties of the fabric (Y. Li, Dai, & Textile Institute, 2006). Accordingly, scientific understanding and knowledge in physical properties of the fabric are essential to engineer comfort of clothing.

Smart clothing has to withstand the physical changes during wearing or laundering in order to maintain consistent functions as a garment and as an electronic device. As shown in Figure 2- 6, physical property has been repeatedly addressed as an important factor in a practical sense (Chae, et al., 2009; Dunne & Smyth, 2005; Knight & Baber, 2005; McCann, et al., 2005; S. Park & Jayaraman, 2003). Based on its performance in mechanical deformation and thermal management, smart clothing has to be assured in terms of physiological appropriateness. Also, electrical functions must not be damaged or lose efficiency by physical interruptions or physiological waste from the wearer.

2.3.1. Mechanical Deformation

A garment interacts with an underlying body when it is worn. As the body moves, it is natural for the garment fabric to conform to the same movement. Depending on the direction of forces, as shown in Figure 2- 13, mechanical deformations of the fabric are divided into stretching, shearing, bending, and compression (De Boos & Tester, 2005). Mechanical deformations have been investigated to study fabric hand, which refers to the sensation felt when the fabric is touched. Researchers believed that fabric hand could be estimated from mechanical measurements (Behery, 2005). Several instruments have been designed, redesigned, and developed to measure fabric mechanical properties.

Peirce pioneered the study of physical characteristics of fabrics. He initiated the first experimental work on the objective measurement of fabric mechanical properties in 1930s

(Peirce, 1930). A number of measures have been identified and investigated to explain stiffness, hardness, and friction of fabrics. Then, developed in 1970s, Kawabata Evaluation System for Fabrics (KES-F) and Fabric Assurance by Simple Testing (FAST) system are the instruments commercially available in many fabric testing laboratories (Behery, 2005). KES-F was developed by the Textile Machinery Society of Japan while they were trying to standardize fabric hand evaluation (Kawabata & Hand Evaluation and Standardization Committee., 1980). They defined 16 mechanical properties and developed instruments to measure these properties. FAST system was established by an Australian company, CSIRO Textile Fibre and Technology, in an attempt to help garment manufacturers select a fabric based on its functional and aesthetic performances and assure the quality of garment tailoring (Fan, Yu, Hunter, & Batra, 2004). FAST systems are based much on Peirce's findings.

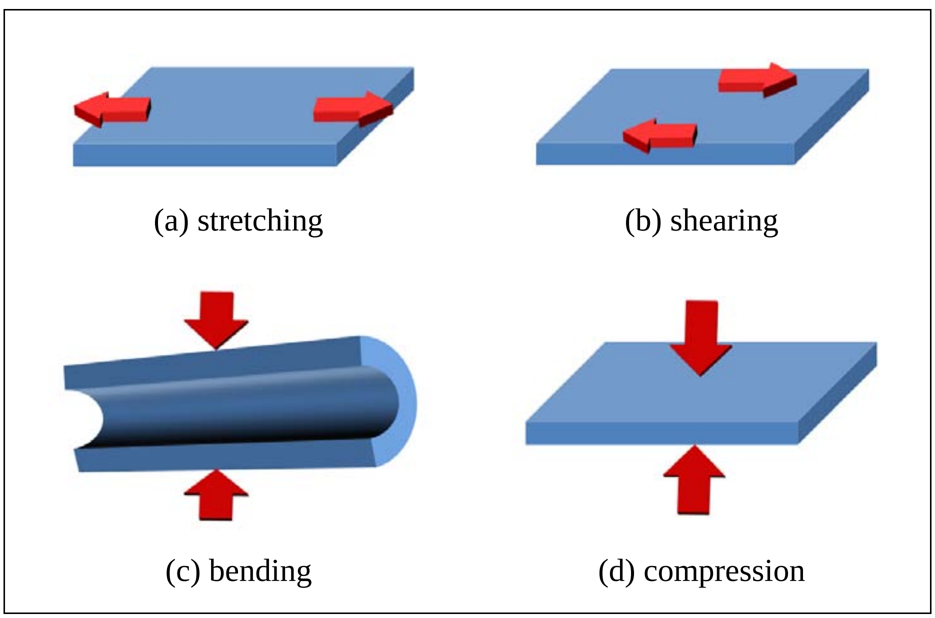


Figure 2- 13. Mechanical Deformations of Fabric

Stretching creates a length greater than its original (Figure 2- 13a). Tensile test is common for fibers or yarns as well as fabrics as this property is considered a very basic characteristic of polymeric materials. A stress-strain (load-extension) curve is obtained after extending and relaxing the fabric. Several values (Table 2- 5) are calculated from this curve to characterize tensile properties (De Boos & Tester, 2005; Kawabata & Hand Evaluation and Standardization Committee., 1980; Peirce, 1930). Known as Young's modulus, Peirce's extensibility has been widely used, which refers to the very initial slope of the stress-strain curve. Formability is related to a complex deformation in which tensile, bending, and compression forces are involved, which can be calculated from the bending rigidity multiplied by the extensibility.

Table 2- 5. Tensile Characteristic of Fabric

System	Parameter	Description	Unit
Peirce	Extensibility (*q'*)	Initial ratio of tensile stress to strain	gf /cm^2
KES-FB1	Linearity (*LT*)	Linearity of tensile behavior	(none)
	Tensile Energy (*WT*)	Energy required for the extend unit area	gf·cm/cm^2
	Resilience (*RT*)	Tensile recovery behavior	%
FAST-3	Extensibility (*E*)	Extensibility of a fabric under loads	gf /cm^2
	Formability (*F*)	In-plane compressibility	cm^2

Shearing is a deformation in which parallel planes remain parallel, but are shifted in a direction parallel to them (Figure 2- 13b). It is a good indicator of structural freedom of woven fabrics in which warp yarns and weft yarns are orthogonally interlaced. According to De Boos and Tester (De Boos & Tester, 2005), shear rigidity is one of the principle determinants of garment ease as it is closely related to fabric deformation into a three-dimensional shape. Shear stiffness obtained from the FAST system is not directly comparable to KES-F as they take distinct perspectives from each other to measure shear deformation. FAST measures the strain at constant load and KES-F measures the load at various strains. KES-F sets 0.5° and 5° as the standard shear angles, while FAST system has the bias direction which is 45° angle. Characteristic values for shearing are defined in Table 2- 6 (De Boos & Tester, 2005; Kawabata & Hand Evaluation and Standardization Committee., 1980).

Table 2- 6. Shearing characteristic of fabric

System	Parameter	Description	Unit
KES-FB1	Shear stiffness (*G*)	Shear force for unit angle per unit length	gf/cm·degree
	Hysteresis (*2HG*)	Hysteresis at shear angle = 0.5°	gf/cm
	Hysteresis (*2HG5*)	Hysteresis at shear angle = 5°	gf/cm
FAST-3	Bias Extensibility	Extensibility to 45° direction	gf /cm^2
	Shear Rigidity	Load required to deform unit width of fabric to unit strain	gf/cm

Bending is a fabric movement that causes the formation of a curve (Figure 2- 13c). The way in which the fabric drapes or hangs depends largely on its bending stiffness. Peirce considered fabric bending properties as a key component and developed a number of tests to measure the bending stiffness (Behery, 2005). For both Peirce and FAST system, bending stiffness is derived from bending length. Bending length is the fabric length bending under its own weight and it can be measured by Cantilever methods (ASTM D-1388; British Standard Method 3356). On the other hand, KES-F observes the fabric bending created by additionally applied forces. The relationship between the applied force and resulting curvature is analyzed to quantify bending hysteresis as well as bending rigidity (Kawabata & Hand Evaluation and Standardization Committee., 1980). Characteristic bending parameters are listed in Table 2- 7 for different instrumentation (De Boos & Tester, 2005; Kawabata & Hand Evaluation and Standardization Committee., 1980; Peirce, 1930).

Table 2- 7. Bending characteristic of fabric

System	Parameter	Description	Unit
Peirce	Bending Length (*C*)	Resistant length to bending at 41.5°	cm
	Flexural Rigidity (*G*)	Actual force required for bending	g·cm
	Bending Modulus (*q*)	Degree of cohesion between fibers/yarns	g/cm^2
KES-FB2	Bending Rigidity (*B*)	Bending rigidity per unit length	$gf{\cdot}cm^2/cm$
	Bending Hysteresis (*2HB*)	Moment of hysteresis per unit length	(none)
FAST-2	Bending Length (*BL*)	Resistant length to bending at 41.5°	cm
	Bending Rigidity (*BR*)	Actual force required for bending	gf·cm

Compression makes fabrics more compact by or as if by pressing (Figure 2- 13d). Compression is more related to the appearance or fabric hand than mechanical performances (De Boos & Tester, 2005). Compression is measured on the fabric after repeated compressions and relaxation. The relationship between the applied pressure and fabric thickness is observed to characterize the compression values (Table 2- 8) (De Boos & Tester, 2005; Kawabata & Hand Evaluation and Standardization Committee., 1980; Peirce, 1930).

Table 2- 8. Compression characteristic of fabric

System	Parameter	Description	Unit
Peirce	Hardness (*H*)	The ratio of the difference in pressure to the difference in thickness	g/cm^3
	Compression Modulus (*h*)	Difference in thickness divided by the original thickness	g/cm^2
	Thickness (*d*)	Thickness at zero force	cm
	Density (ρ)	Weight divided by thickness	mg/cm
KES-FB3	Linearity (*LC*)	Linearity of compression behavior	none
	Compression Work (*WC*)	Energy required for the compression	$gf{\cdot}cm/cm^2$
	Resilience (*RC*)	Compression recovery behavior	%
	Thickness (*T*)	Thickness at pressure 0.5 gf/cm^2	mm
	Weight (*W*)	Weight per unit area	mg/cm^2
FAST-1	Surface Thickness (*ST*)	Thickness difference of between the loads of 2 g/cm^2 and 100 g/cm^2	cm

A fabric or clothing undergoes the combinations of these mechanical deformations produced by wearer's posture and movement. Laundering must create even more harsh deformations. Smart clothing must resist these physical attacks to avoid any damage on its appearance and function. Also, the electrical component itself is deformable enough to assure the comfort so that the wearer can move around without any restriction.

2.3.2. Heat and Moisture Transfer

Metabolites are physiological wastes produced by a human body, which include heat and sweat. The human temperature is kept at ~37°C for the core body and ~33°C for the skin (Yu & Textile Institute, 2006). In order to maintain this temperature in thermal balance without sweat generation, the amount of heat production and loss must be equal (Y. Li, et al., 2006). Since heat is generated by metabolism and physical exercise, the body tries to dissipate the heat through conduction, convection, radiation, and evaporation. Due to sweating and its evaporative heat loss, heat transfer is very closely related to moisture transfer. Sweaty contamination may disturb the functioning of electrical components as they are usually very fragile to moisture.

Heat and moisture transport can be measured from the simulated skin model instrumentation (Figure 2- 14), called a sweating hot plate (ASTM D-1518). Heat transfer is the measure of the heat flow from the heated plate simulating human skin, through the fabric material, into the environment. Thermal and evaporative resistance of the fabric can be calculated from

Woodcock's equation described below (Woodcock, 1962). Other comfort parameters, such as insulation value (*Clo*) and permeability index (I_m), are also derived from the equation (1).

$$H_t = H_c + H_e = \frac{(T_s - T_a)A}{R_c} + \frac{(P_s - P_a)A}{R_e} \tag{1}$$

where, H_t = total heat transfer, H_c = thermal heat transfer, H_e = evaporative heat transfer, T_s = skin temperature, T_a = ambient temperature, P_s = skin vapor pressure, P_a = ambient vapor pressure, A = area of skin contact, R_c = thermal resistance, and R_e = evaporative resistance

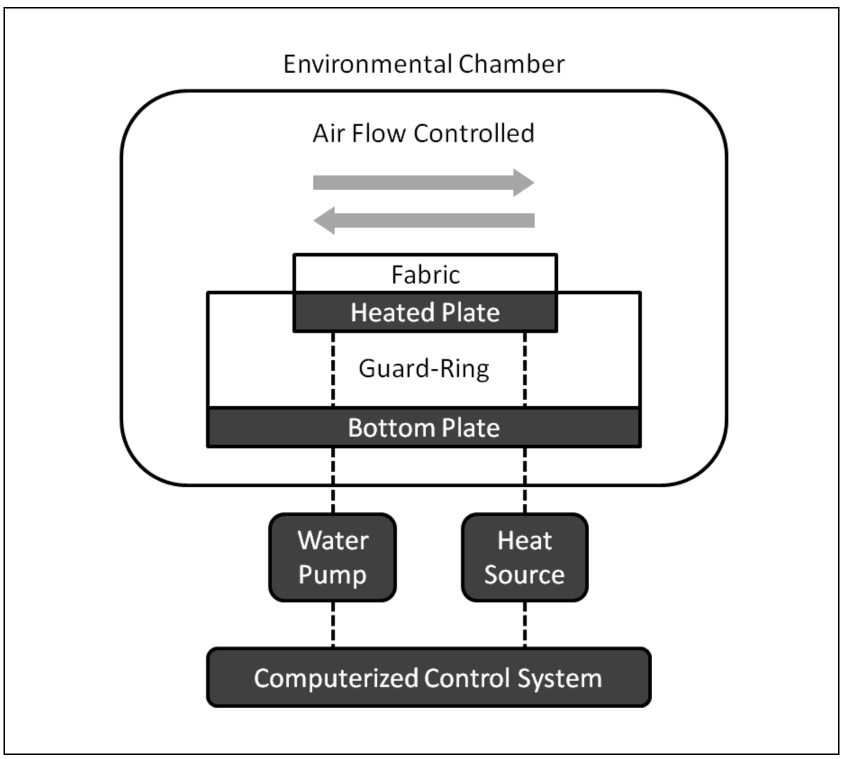


Figure 2- 14. Sweating Hot Plate Instrumentation
(Woo & Barker, 1988)

Moisture vapor transfer rate (MVTR) is a measure of breathability which regulates the dissipation of moisture vapor from a saturated microclimate to the ambient atmosphere. This is a critical determinant of clothing comfort, especially in a condition that involves sweating. The build-up of humidity between a clothing layer and sweat-wetted skin is known to contribute to sensations of dampness and clamminess (Prahsarn, Barker, & Gupta, 2005). According to Yoon and Buckley (Yoon & Buckley, 1984), moisture vapor transport through the fabric at a steady-state is determined largely by its thickness and porosity.

The liquid moisture management performance of the fabric is a totally different mechanism from that of moisture vapor. A fabric draws liquid moisture through capillary tubes in the structure by capillary attraction even though the driving pressure gradient is zero or negative. This is called wicking and the direction of moisture movement is horizontal, vertical, or both. Wicking test is conducted with one end of a fabric strip clamped vertically and the other dangling end immersed in distilled water. The height to which the water is transported along the strip is measured in different time domains (R. L. Barker, Scruggs, & Shalev, 2000 Spring). A higher wicking value refers to greater liquid moisture transport ability. According to Yoo and Barker (S. Yoo & Barker, 2004), wicking results from complex combinations of the properties such as absorbent capacity, absorption rate, and evaporation.

The primary fabric characteristic affecting heat and moisture transfer is thermal conductivity. It refers to the ability of a fiber material to conduct heat and is a reciprocal of thermal resistivity. While fibers have a similar range of values in terms of thermal conductivity, there are differences between them with cotton being the most conductive and polypropylene being the least conductive (Watkins, 1995). However, according to Woo and Barker (Woo & Barker, 1988), thermal performance of a fabric is decided more by structural properties than material characteristics. The structural properties include air permeability, fiber volume fraction, optical porosity, and thickness as listed in Table 2- 9 (R. L. Barker, et al., 2000 Spring; Prahsarn, et al., 2005).

Table 2- 9. Primary Characteristics Affecting Thermal Property of the Fabric

Property	Description	Unit
Air permeability	Air resistance of the specimen when a constant rate of air flow was passed through a known area of fabric into the atmosphere	$cm^3/cm \cdot min$
Fiber volume fraction	Fraction volume of fibers over the total volume	%
Optical porosity	Transmittance of visible light through the fabric	%
Thickness	Fabric thickness at 0.5 gf/cm^2 pressure (KES-FB3)	mm

2.3.3. Comfort of Smart Clothing

To assure the clothing comfort, an investigation on physiological demands of the body has been highlighted as essential design considerations in smart clothing. According to McCann

(1999), these demands are protection, anthropometry, ergonomics of movement, thermo-physiological regulation, and psychological considerations. Bryson (2007) addressed water regulation, thermal regulation, and physical sensation. These issues are joined together into thermal comfort (heat and moisture regulation), tactile comfort (surface mechanics and physical sensation), and mobility (movement, fit, and size).

Thermal discomfort becomes apparent if the thermal equilibrium is upset and the body feels too hot or too cold. The characteristics of clothing, climate conditions, and level of physical activity need to be considered to assess thermal comfort of a garment system (Yi Li & Wong, 2006). However, an additional factor must be involved in smart clothing, heat generated by electrical components. It may break thermal equilibrium and damage to other electrical components if auxiliary cooling does not take place. For example, a printed circuit board made up of layers of impermeable resin prevents evaporative heat loss and traps heat inside the garment system. Trapped heat and the resulting moisture may cause a short circuit or corrode conductive materials (Dunne & Smyth, 2005). Both physical impacts of electrical functionality on the human body and the impacts of human physiological reaction on an electrical component should be taken into account.

Tactile discomfort is caused by the interaction between human skin and a fabric surface as the contact stimulates various sensory receptors on the skin. It is known that overall tactile comfort of clothing is related more to heaviness or tightness than the feelings of prickliness, itchiness, or roughness (R. Barker, 2002; Y. Li, et al., 2006). The pressure caused by heaviness and tightness can interfere with mobility of the wearer. Mobile restriction brings about unwanted heat production due to metabolic rate increasing when the body tries to move against heavy or stiff clothing. Also, if a body is exposed to excessive loads, muscle fatigue occurs. Continuous high pressure can develop various tissue lesions, such as pressure sores and ulcers (Y. Li, et al., 2006). Since the level of tolerable pressure and bulk varies at different locations on the body (Watkins, 1995), electrical components must be situated at the appropriate position on the body.

Appropriate location may reduce the burden or abrasion on the skin surface and preserve the thermal, tactile comfort and mobility. Dunne and Smyth (Dunne & Smyth, 2005) suggested places in the garment structure where some volume or stiffness is acceptable; shoulder, upper back, and abdomen. The selection of the location dramatically depends on wearer's gender, age and nature of functions. For example, upper chest of the male and upper back of the young is a planar surface, while it is not for the female and elderly, respectively. Also, if an electrical component has to be located in a specific body area for sensing or actuating, this must be considered as well.

Smart clothing requires special care to manage electrical components and to maintain the same standards of comfort as ordinary clothes. The wearer should not be limited in comfort or mobility as a result of smartness in clothing (Bryson, 2007; Dunne & Smyth, 2005; McCann, et al., 2005). At the same time, electrical devices must not be damaged or lose the efficiency by any mechanical interruption (*e.g.* posture or movement) and body wastes (*e.g.* sweat or heat) that wear creates.

2.4. Wireless Communication

The main objectives of transmission in smart clothing are to supply electric power and to transfer data signals through the medium over a distance. Typical examples of such media are metals for wired transmission and air for wireless transmission. Wiring is a traditional way to form a path directing the transmission of energy. Wired interfaces have used from the view point of the communication quality so far. Currently, however, wireless communication prevails due to improved reliability and absence of physical restriction. Wireless data link has enough reliability and even has advantages over the wired link for proximity communication (Ishikuro, Miura, & Kuroda, 2007).

2.4.1. Wireless Network

Wireless transmission is the transfer of electrical energy over a distance without the use of electrical conductors. Despite that wiring supplies more reliable transmission, users do not like wires all over their body which might get caught, broken, and tangled. Wireless networks are generally implemented with some type of remote information transmission system that uses electromagnetic waves (*i.e.* radio frequency, microwave, and infrared).

Wireless Local Area Network (LAN) is covering geographic areas such as a group of buildings. This gives people the mobility to move around within a local coverage area and still be connected to the network. Based on IEEE 802.11 standard, wireless LANs are characterized by higher data-transfer rates. Wireless LANs have become popular to provide the internet service to laptop computers, which is called Wi-Fi™. Wi-Fi™ is increasingly used as a synonym for 802.11 LANs.

Wireless Personal Area Network (PAN) interconnects electronic devices within a relatively small area, generally within reach of a person. Bluetooth™ and ZigBee™ are the most well known commercialized PANs. They use short length radio waves around 2.4 GHz in the industrial, scientific, and medical (ISM) radio bands. Invented by telecom vendor Ericsson in 1994, Bluetooth™ is a wireless technology standard to exchange data over short distance. It is following IEEE 802.15.1 standard and used for the purpose to connect several electronic devices eliminating cables between them. ZigBee™ is a low-cost and low-power wireless networking proprietary protocol using small digital radios based on IEEE 802.15.4 standard. With low data rate, this technology provides simpler and less expensive networking compared to Bluetooth™. ZigBee™ is often applied to remotely control residential or commercial sensors. ZigBee™, Bluetooth™, and Wi-Fi™ are compared in Table 2- 10 (Price, 2007).

Recently, prompted by the rapid growth in wearable technology and smart clothing field, the concept of wireless Body Area Network (BAN) has been attracted much interest (Lee, et al., 2009; Yang, 2006). Wireless communication in a few centimeter ranges is realized between a set of compact intercommunicating devices either worn or implanted in the human body. This short range communication is due to low power consumption since the devices have to be powered by small-sized batteries (Lee, et al., 2009). Initial applications of BAN have been expected to appear primarily in the healthcare domain, especially for continuous monitoring and logging vital parameters of the patients suffering from chronic diseases. Other applications of this technology include sports, military, or security. BAN technology is still in its primitive stage and is being widely investigated.

Table 2- 10. Types of Wireless Network

	ZigBee™	Bluetooth™	Wi-Fi™
Logo			
Type	WPANs	WPANs	WLANs
Standard Protocol	IEEE 802.15.4	IEEE 802.15.1	IEEE 802.11
Radio Band	2.4 GHz	2.4 GHz	2.4 GHz
Date Rate	~250 Kb/s	~1,000 Kb/s	~11,000 Kb/s
Distance	up to 30 m	up to 50 m	up to 132 m
Major Application	Remote Control	Electronic Connection	Wireless Internet

2.4.2. Radio Frequency Identification (RFID)

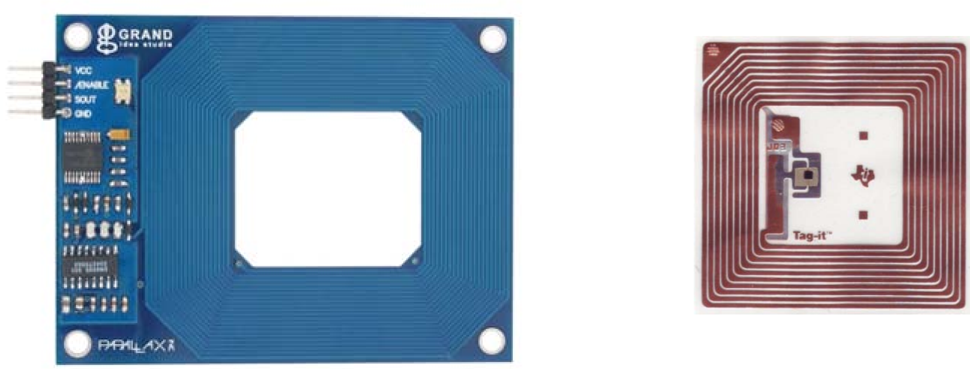
An increasing number of wireless systems are based on radio frequency technology (Mayes & Markantonakis, 2008). RFID technology is fast becoming a part of our daily lives for example, contactless smart cards for immediate identification or payment in short-distance public transport. RFID has a huge advantage in terms that it operates without galvanic contacts. Data exchange is highly secure and reliable. A RFID system has a semi-permanent product life because it is reprogrammable and strong against environmental conditions such as dirt and damp. The global RFID market is valued at $ 2.5 billion in 2006 and is expected to increase to $ 25 billion by 2016 (Mayes & Markantonakis, 2008).

Table 2- 11. Comparison of RF Bands

	135kHz	13.56MHz	900MHz	2.45GHz
Distance	< 60cm	~ 60cm	3m-10m	~ 1m
Cost	Expensive	Less expensive	Least expensive	Expensive
Reading speed	Slow -- Fast			
Power consumption	Low -- High			
Application	Animal identification	Access control, Payment	Real-time positioning	Bluetooth, ZigBee

Thanks to recent advances in cost reduction, potential applications of RFID are almost endless. Implanted RFID tags in livestock allow farmers to identify their animals and this can be applied to accommodate convenience and efficiency in consumer transactions as well. Manufacturers can easily locate items necessary to fill orders without incurring undue managerial or labor time. Retailers can use RFID to manage inventory, to monitor shelves, and to track store trolleys in the supermarket. Consumers can check out merchandise with contactless payment by holding their credit card near a special reader instead of swiping it or handing it to a clerk. RFID is able to control an authority to access to areas in a given physical facility or resources in a computer-based information system. RFID Systems engaged with higher frequencies can realize real time positioning by analyzing signal strength. Most common radio bands in standard RFID systems are shown in Table 2- 11. The distances, costs, and speed vary depending on the electromagnetic spectrum involved.

An RFID system is made up of a transponder and a reader (Figure 2- 15). Data is stored on an electronic data-carrying device, the transponder. The reader can access stored data in the transponder by physically approaching it. Transponders have two types; passive and active. A passive transponder is not equipped with its own power source. Power required for the operation must be supplied by the reader. As a result, passive RFID tags can be as small as 4 millimeters square and thinner than a average sheet of bond paper (Price, 2007). Operated by built-in batteries, an active transponder has a larger output, therefore further distance to communicate.



(a) reader (b) transponder

Figure 2- 15. RFID System

The biggest barrier of RFID technology is that radio waves cannot be read through metal. Metallic objects near the reader and transponder interfere with the signal transfer between them (Finkenzeller & NetLibrary Inc., 2003). In addition, reader collision occurs when the signals from two or more transponders overlap, which interferes with the signal transfer disabling the capability of the reader. Ease of access could also be a problem. Since the transponders can be read without being swiped or obviously scanned, anyone with a reader might be able to read the information embedded in the transponder without the owner's knowledge. High-gain antennas can be used to extend the communication range, leading to privacy problems.

2.4.3. Inductive Coupling

The connectivity between the passive transponder and the reader is achieved through inductive coupling. Two conductors are referred to as 'inductively coupled' when one wirelessly transfers electrical energy to the other by means of a shared magnetic field (Mayes & Markantonakis, 2008). Inductive coupling is caused by mutual induction between two inductors positioned so that energy is transferred by magnetic linkage. As shown in Figure 2-15, an inductively coupled system uses a coil antenna which can cover less than 1 meter distance to transfer data and power (Finkenzeller & NetLibrary Inc., 2003). An inductively coupled transponder comprises an electronic data-carrying device, usually a single microchip, and a large coil that functions as an antenna. An inductively coupled reader can provide electrical power to the transponder and read the data from it. Attached to a reader unit, a subcarrier contains various electronic units to accommodate the reliable data transmission.

The coupling efficiency between two coil inductors dramatically improves if resonance is involved. Resonance occurs as electrical energy is stored in two different ways: electric field and magnetic field. A LC circuit (Figure 2- 16), consisting of an inductor (L) and a capacitor (C), resonates at a specific frequency when its inductive reactance and capacitive reactance are matched. The circuit impedance maximizes at the resonant frequency. Resonant frequency of a parallel LC circuit is known as follows.

$$F_R = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

where, F_R = resonant frequency, L = inductance, and C = capacitance.

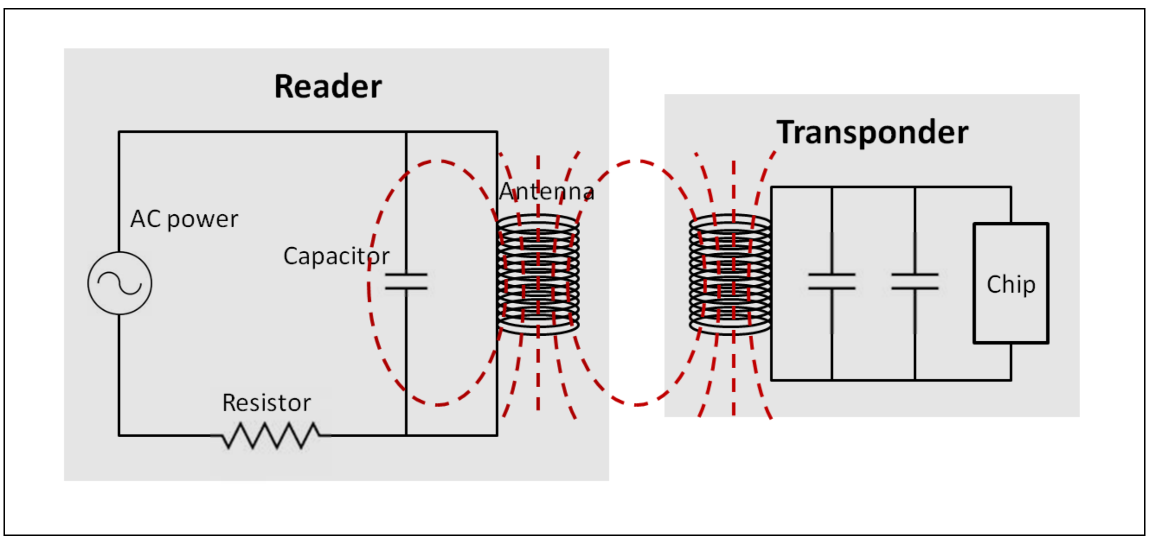


Figure 2- 16. LC Circuit Inductively Coupled

An inductor stores energy in its magnetic field depending on the electric current through it, and a capacitor stores energy in the electric field depending on the voltage across it. If the inductor and the capacitor are connected together, electric current alternates between them at the circuit's resonant frequency, which means that the circuit can store electrical energy vibrating at the resonant frequency. If it were not for dissipation, the resonant effect would continue forever.

Inductively coupled transponders are almost always operated passively, which means that the energy needed for the operation has to be provided by the reader. To supply power to the transponder, the reader's antenna coil has to generate an electromagnetic field of high frequency and strong enough to penetrate the cross-section of the coil area and the area around the coil. By induction, the voltage is generated in the transponder's antenna coil. A small part of the electromagnetic field emitted from the reader's antenna coil penetrates the transponder's antenna coil some distance away. Induced voltage is rectified to serve as the power supply for the transponder.

As well as to provide power, the alternating field can also be used to transfer data (Yang, 2006). A resonant transponder, which has the self-resonant frequency corresponding to the reader's resonant frequency, can cause the feedback on the reader's antenna if it is placed within the magnetic field. By switching a load resistor on and off at the transponder's antenna, voltages at the reader's antenna can be modulated. If the timing with which the load resistor is switched on and off is controlled by data, this data can be transferred from the transponder to the reader. In practice, due to the weak coupling between the antennas, the voltage fluctuations at the reader's antenna are too small to present the useful signal. In order to detect this slight voltage change, highly complicated circuitry is adopted including band-pass (*BP*) filtering, integrated circuit (*IC*), and demodulator (Finkenzeller & NetLibrary Inc., 2003).

The layout of two coils can serve as a transformer to control the transferring efficiency between the primary coil in the reader and the secondary coil in the transponder. The efficiency of power transfer between the antenna coils is proportional to the operating frequency (f), the number of windings (n), the radius of the coil (R), the angle of the two coils relative to each other (θ), and the distance between the two coils (d) (Finkenzeller & NetLibrary Inc., 2003; Mayes & Markantonakis, 2008). In general, the field strength is almost uniform at short distances ($d < R$).

Inductive coupling is good to transfer electrical power and data signals wirelessly 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 (Finkenzeller & NetLibrary Inc., 2003). 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 (J. Yoo, et al., 2010) as it favors relatively lower frequency−typically 13.56 MHz. Sharing the short length radio waves (~2.4 GHz), ZigBee or Bluetooth™ may interfere with wireless LANs.

2.4.4. Application on Smart Clothing System

The potential application of wireless technologies in smart clothing is virtually wide open, especially in the medical and healthcare fields. The capability to track and monitor patients outside of a hospital or medical facility is expected to reduce hospital stays and cost of medical care. One example is the Wireless Medical Telemetry System (WMTS) using three frequency bands; 608 to 614 MHz, 1.395 to 1.4 GHz, and 1.429 to 1.432 GHz (Price, 2007). These bands are reserved to receive or transmit information on health or medical status of the patients.

Due to wideband, low-power, and low-cost interfaces, inductively coupling is suggested for proximity communication in portable systems. Communication distance, signal frequency, antenna size, and power consumption are important design parameters. A larger antenna which creates greater inductance can increase the communication distance (Ishikuro, et al., 2007; Lee, et al., 2009). As shown in Figure 2- 17, larger inductors take advantages in transmission coefficient and communication distance. Preferable for strong signal received, high frequency signal results in higher data transfer rate (Ishikuro, et al., 2007). Antenna size and frequency, however, increase power consumption which is another critical issue in portable systems.

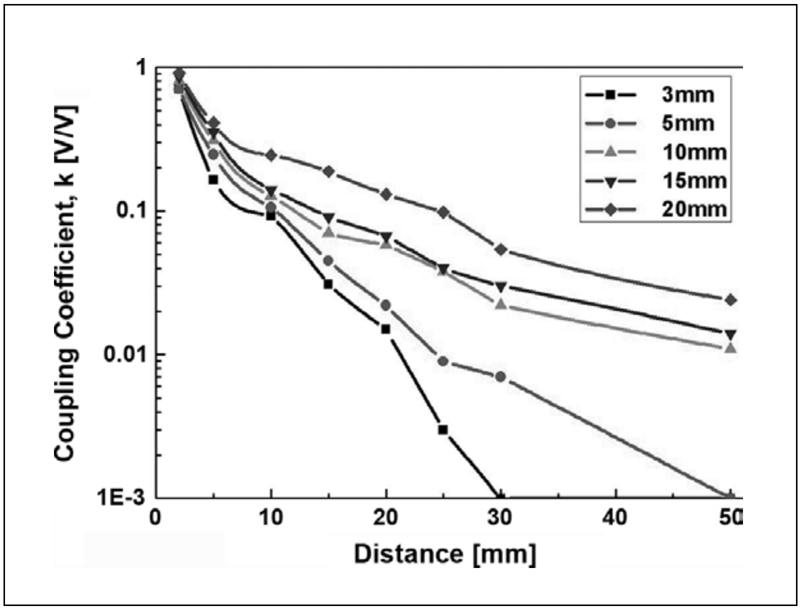


Figure 2- 17. Inductor Size and Transmission Coefficient (Lee, et al., 2009)

Antennas integrated into a flexible substrate have issues with the change of shape and size as the substrate may experience mechanical deformations. Wireless communication would be disturbed because the magnitude of electromagnetic field is influenced by the conditions of antenna (Finkenzeller & NetLibrary Inc., 2003; Mayes & Markantonakis, 2008). The transmission would be also interrupted by relative locations of the antennas, which might change if the transponder and reader exist on the separable planes. Variations in characteristics of fabric substrate, number of fabric layers, and antenna loop designs can create different coupling effects.

Inductive coupling has been more popularly adopted for inductive sensing rather than wireless communication. Sensitivity of antenna condition is preferable when the antenna is used as an electronic proximity sensor, which detects movement or displacement. A series of inductor antennas can be used as a sensor in wearable healthcare system (Kang, 2006; Merritt, 2008). As the antennas were integrated to stretchable fabrics, the sensor can monitor the respiration of the wearer (Figure 2- 18).

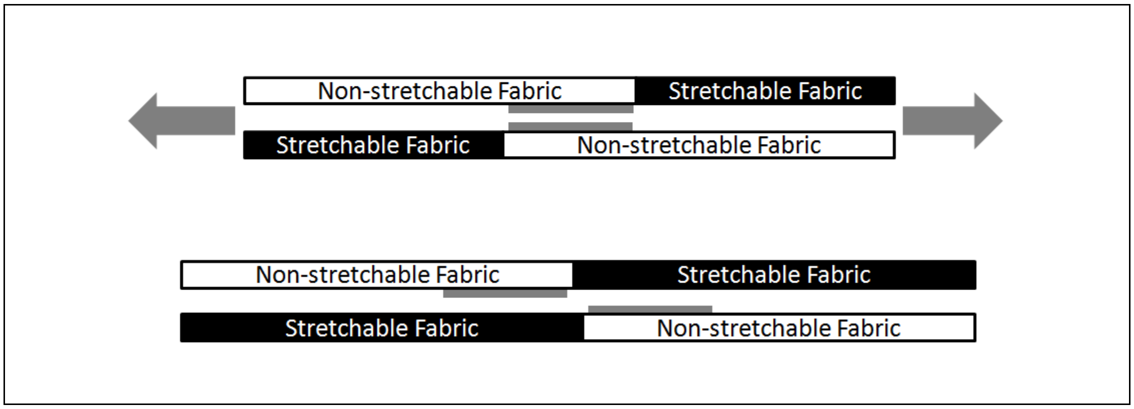


Figure 2- 18. Design of Respiration Sensor Using Inductive Coupling

Another researcher (Lee, 2009; Lee, et al., 2009) used inductively-coupled antennas to replace wires in a wearable system. Appropriate antenna geometry and low power consumption were highlighted. As an antenna grows in size, inductance increases and self-resonant frequency decreases. The tradeoff between inductance and resonant frequency is equivalent to the tradeoff between data rate and communication distance and both are very important parameters in the wireless communication system. A 10mm × 10mm square inductor was suggested with 2μH inductance and its self-resonant frequency was reported as 400MHz. The specification of inductor antennas in literatures is compared to ISO 15693 in Table 2- 12.

Based on literature, the experiments were designed to estimate wireless transmission and comfort characteristics of fabric antennas. Antennas were established on fabric substrates by means of conductive printing. Electrical and mechanical performance was measured varying in fabric substrates and coating materials while transmission performance was measured changing physical conditions the fabric antennas were situated. Electrical and mechanical characteristics of fabric antennas were observed to test the potentials as an antenna and to ensure the comfort, respectively. Transmission characteristic was tested whether the antennas were appropriate for clothing environment.

Table 2- 12. Antenna Design Spec

	Kang (2006)	Lee et al. (2009)	ISO 15693
Application	Sensor	Transmission	RFID
Conductive path width (mm)	0.4	1	1
Path spacing (mm)	0.8	1	~ 0.1
Antenna size (mm×mm)	60 × 40	10 × 10	75 × 45
Windings	6	4	7
Frequency (Hz)	–	400 M	13.56 M
Distance (mm)	2	20	50

It was seen from the literature that smart clothing is challenged by conflicts between multidimensional usability factors. Based on various usability studies, physical characteristics and relevant comfort issues were discussed. Wireless transmission using inductively coupled antennas was selected as one of the solutions to overcome physical restrictions. Due to the multidisciplinary characteristics, smart clothing has been investigated for electrical performance as an electronic and for comfort as a garment, separately so far. This makes it difficult to understand the conflict that inevitably exists between them. Recognized a trade-off between electrical performance and comfort, this research analyzes the trade-off and seeks the balance to optimize the overall usability. This would help users and researchers of smart clothing understand smart clothing closer to reality.

CHAPTER III. METHODOLOGY

The research was designed in system approach to incorporate multiple fabric layers in smart clothing using wireless link. Psychological, physical and functional usability was considered. Each experiment was planned to obtain fundamental basis to validate the feasibility of hypotheses.

3.1. Research Questions

To guide the investigation, the following research questions were developed;

1. How does silver conductive ink perform when printed on a variety of fabric substrates?
2. Which types of coating layers are valid to support antenna performance so that the physical characteristics of the fabric substrates are not impaired?
3. How do physical conditions affect the wireless transmission between inductively-coupled fabric layers printed with silver conductive ink?

3.2. Experimental Design

3.2.1. Experimental Design I

Covering the first and second research questions, the first set of experiments investigated the printability of silver conductive ink on different fabric substrates and with coating materials.

Denim, broadcloth, and single jersey fabrics were chosen to represent outerwear, innerwear, and underwear, respectively. Three different coating materials, acrylic resin, polyurethane, and silicone, were selected as they are common for conventional printed circuit boards (PCBs). As shown in Table 3- 1, experiments were conducted in full 3×3 factorial design to study the effects of substrates and coatings and their interactions. Each treatment was applied with 4 to 11 replications (Table 3- 2) for statistical analysis. Total experimental runs were 62.

Table 3- 1. Experimental Design I

Factor	# Levels	Levels
Fabric substrate	3	Denim, Broadcloth, Single jersey
Coating	3	Acrylic resin, Polyurethane, Silicone
Total	9	

Table 3- 2. Full Factorial Design Table

Runs	Replications	Factors	
		Fabric substrate	Coating
1-5	5	Denim	Acrylic resin
6-11	6	Denim	Polyurethane
12-17	6	Denim	Silicone
18-21	4	Broadcloth	Acrylic resin
22-28	7	Broadcloth	Polyurethane
29-35	7	Broadcloth	Silicone
36-41	6	Single jersey	Acrylic resin
42-51	10	Single jersey	Polyurethane
52-62	11	Single jersey	Silicone

Resistance (R) and inductance (L) of the printed inductor were measured as a response to evaluate its possibility as an antenna for a wireless transmission. Mechanical characteristics of the fabric antennas were tested and compared to those of bare fabric substrates in order to estimate the restrictions newly added. The mechanical tests included tensile, bending, and compression tests as they are major physical deformations to accommodate the mobility. Air permeability was chosen due to its huge contribution to thermal comfort.

3.2.2. Experimental Design II

In order to answer the third research question, the second set of experiments investigated the influence of physical conditions on wireless transmission between inductively-coupled fabric layers. The most promising fabric substrate and an appropriate coating were selected from the first experimental results. Scattering parameters were recorded as a response to see how well the antennas transfer the signal to each other under the physical limitations which simulates wear situations.

The physical limitation included distance, displacement, stretching and bending. Distance refers to the space between two antennas, while displacement indicates the coplanar movement of the antenna. Based on the amount of typical garment ease and fit, levels of the distance and displacement were selected from 0 to 5.18 cm (from 0 to 2 inches). Regarding the measures at major joints in human body (e.g. elbow, knee, spine) and extensibility of the selected fabric substrate, levels of stretch were decided up to 10% extension. Bending curvature was selected regarding garment curvatures (e.g. torso, sleeves) and the measures in KES system (Kawabata & Hand Evaluation and Standardization Committee., 1980).

Single effect of each physical condition was analyzed with separate linear regression models. Experimental design is summarized in Table 3- 3. Experiments on distance and displacement were run with 12 replications, which meant scattering parameters were captured from 12 different fabric antennas. The number of replication was 6 and 8 for stretching and bending tests, respectively.

Table 3- 3. Experimental Design II

Factor	Levels	# Levels	Replications	# Runs
Distance	0, 0.63, 1.27, 2.54, 5.18 (cm)	5	12	60
Displacement	0, 0.63, 1.27, 2.54, 5.18 (cm)	5	12	60
Stretching	0, 5, 10 (%)	3	6	18
Bending	0, ±0.25, ±0.50 (K)	5	8	40

The physical limitation included distance, displacement, stretching and bending. Distance refers to the space between two antennas, while displacement indicates the coplanar movement of the antenna. Based on the amount of typical garment ease and fit, levels of the distance and displacement were selected from 0 to 5.18 cm (from 0 to 2 inches). Regarding the measures at major joints in human body (elbow, knee, spine) and extensibility of the selected fabric substrate, levels of stretch were decided up to 10% extension. Bending curvature was selected regarding the measures in KES system (Kawabata & Hand Evaluation and Standardization Committee., 1980).

3.3. Materials

3.3.1. Conductive Ink and Coating Materials

Specification of the material is listed in Table 3- 4. Screen-printable silver ink was used to print antenna, which contains 60% silver and its resistivity was as low as 2.5×10^{-7} Ω·cm. Silver ink consists of silver particles dispersed in polymer binder and these silver particles make contact each other to have good electrical conductivity.

Table 3- 4. Material Specification

	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)	70 ±7	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}

Acrylic, polyurethane, and silicone were selected for coating as they are most commonly used in conventional PCBs. Polyurethane was slightly yellowish, and acrylic and silicone were clear. Acrylic and polyurethane were sticky in texture, while silicone was very liquid. As instructed by the manufacturer, ~0.05 g of coating material was brushed over the unit fabric area (1 cm^2). This amount was enough to soak into the fabric structure, even for the heaviest fabric substrate.

3.3.2. Fabric Substrate

Denim, broadcloth, and single jersey were selected to represent each application in everyday wear; outerwear, innerwear, and underwear, respectively. Having lower dimensional stability than woven fabrics, a jersey fabric experiences more tensile and bending deformations, which is beneficial for wearer comfort (Yu & Textile Institute, 2006). Detailed information of fabric substrates is given in Table 3- 5.

Table 3- 5. Fabric Substrate

Fabric	Denim	Broadcloth	Single jersey
Structure	Twill weave	Plain weave	Sheer knit
Fiber contents	Cotton 100%	Cotton 100%	Cotton 100%
Weight (mg/cm^2)	~42.8	~12.8	~15.6
Typical application	Jackets, pants	Dress shirts	T-shirt, underwear

3.3.3. Antenna

Based on the literature (T.-H. Kang, C. R. Merritt, E. Grant, B. Pourdeyhimi, & H. T. Nagle, 2008; T. H. Kang, C. R. Merritt, E. Grant, B. Pourdeyhimi, & H. T. Nagle, 2008; Lee, 2009), the design of antenna was created from a planar spiral inductor (Figure 3- 1), which is 35 mm × 35 mm with 5 turns. Line width was 1mm and so was the space between the lines. Conductive silver ink was manually screen-printed to produce fabric antennas. According to the ink manufacturer's recommendations, a screen was framed with a polyester mesh in 230 threads per inch and silver ink was cured at 90°C for 5-10 minutes after printing.

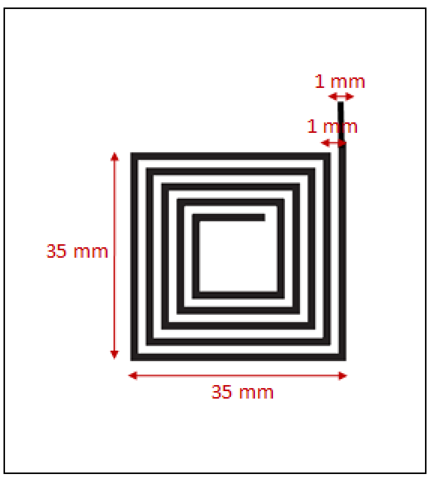


Figure 3- 1. Antenna Design

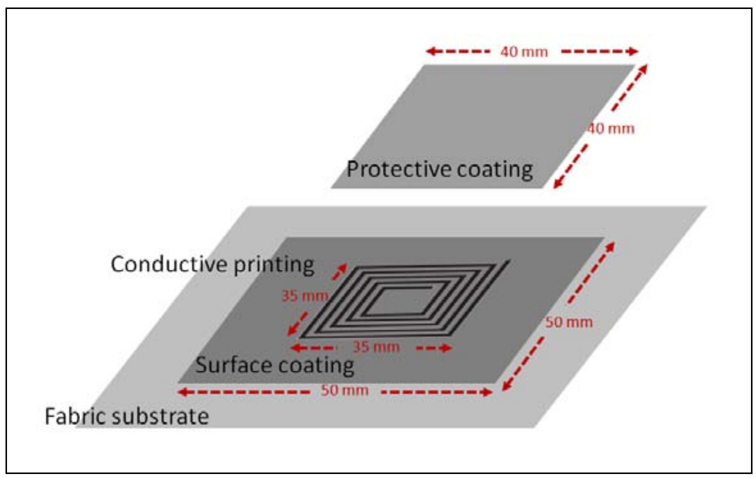


Figure 3- 2. Antenna Structure and Dimension

3.3.4. Printed Structure

As described in Figure 3- 2, the fabric substrate was treated with the coating material before and after the conductive printing in order to improve printability of silver ink and to protect the printed media, respectively. Printability issue arises with silver ink which is not always printed successfully on the fabric substrate. Three possible reasons are as follows.

1) Surface fibers increasing interfacial tension between silver ink and fabric surface: this problem becomes serious with staple fibers which are most of natural fibers, such as cotton or wool. Conductive traces cannot be well-established as silver ink does not adhere to the fabric surface.

2) Rugged surface geography due to cylindrical yarns constructing the fabric: this issue is closely related to the thickness of the yarns involved. Finer yarns must construct much flatter fabric surface than thicker yarns, which is beneficial to conductive printing.

3) Silver ink flowing into the unoccupied space within fabric structure: this is mostly governed by the fabric density. Heavier fabric density can help silver ink not to penetrate into the fabric substrate.

It was also reported by Karaguzel et al. (2008) that conductive printing is optimized when it takes place mostly on the surface. Protective coating layer applied after the printing would keep the conductive traces secure against an electrical short circuit, environment contamination, or mechanical damage. According to previous research (Cho, et al., 2007; Karaguzel, et al., 2009), protective coating dramatically saved conductive prints from losing electrical conductivity after several cycles of mechanical agitation.

3.3.5. Variable Capacitor

Variable capacitors helped the printed antennas resonate at the target frequency which is 13.56 MHz. The capacitance was matched to the following calculation. Variable capacitors (Figure 3- 3), typically less than 10 mm, were prepared in the range of 10-180 pF.

$$F_R = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

where, F_R = resonant frequency, L = antenna inductance, and C = capacitance

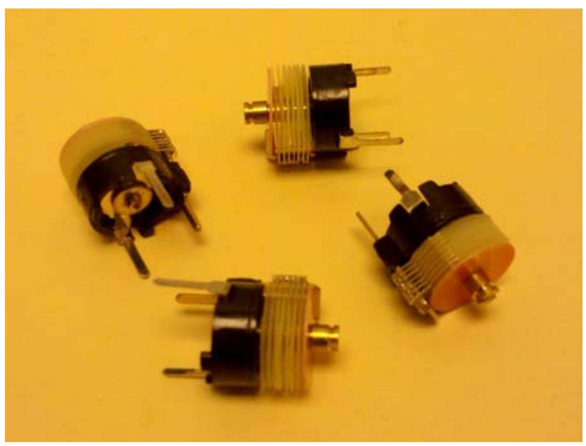


Figure 3- 3. Variable Capacitors

3.4. Measurement

3.4.1. Electrical Performance

As specified in Table 3- 6, electrical performance of the printed antenna was analyzed with resistance (R) and inductance (L) measurements. They were obtained by a network analyzer, Agilent Technologies E5071B ENA series. Resistance is a property to oppose current flow and resistors dissipate electrical energy, while inductance is obtained typically from the behavior of a coil of wire to resist the change of electric current through the coil. Inductors have ability to temporarily store electrical energy in the form of magnetic field surrounding them. As shown in Equation (4), resistance and inductance along with capacitance are important factors to decide impedance (*Z*) for alternating current (Meade & Delmar Learning, 2007).

$$Z = R + j2\pi fL + \frac{1}{j2\pi fC} \tag{4}$$

where, Z = impedance, R = DC resistance, f = AC frequency, L = inductance, C = capacitance, and $j^2 = -1$

Table 3- 6. Electrical Performance Measurements

Measurement	Abbrev.	Description	Unit
Resistance	R	Resistance to oppose current flow	Ω
Inductance	L	Resistance to oppose current change	nH

3.4.2. Mechanical Performance

Mechanical performance of the fabric substrates was tested by observing tensile, compression, bending, and air permeability characteristics. Tensile and compression were measured using Fabric Assurance by Simple Testing (FAST) system, while bending force and air permeability were measured based on ASTM D4032 and ASTM D737, respectively.

Table 3- 7. Mechanical Performance Measurements

Measurement	Abbrev.	Description	Unit
Extensibility	E5	Extensibility at 5 gf/cm	%
	E20	Extensibility at 20 gf/cm	%
	E100	Extensibility at 100 gf/cm	%
Compression	T2	Fabric thickness at 2 gf/cm^2	mm
	T100	Fabric thickness at 100 gf/cm^2	mm
	T2-T100	Compressible thickness	mm
Bending force	Cmax	Maximum force required to bend	N
Air permeability	AP	The amount of air transferred	cm^3/sec·cm^2

FAST-3 system estimates extensibility of fabric at three different load levels (5, 20, 100 gf/cm) in both warp and weft directions. The instrument measures the increase of a 10 cm gauge length of the fabric specimen in millimeters and the fabric extension is displayed directly as a percentage. FAST-1 system uses a non-contact electronic sensor to measure the thickness under two pressures and estimates compression by comparing the thickness, which represents the amount of compressible thickness on the fabric surface (De Boos & Tester, 2005). A digital pneumatic fabric stiffness tester computes the bending force 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. These measurements are listed in Table 3- 7.

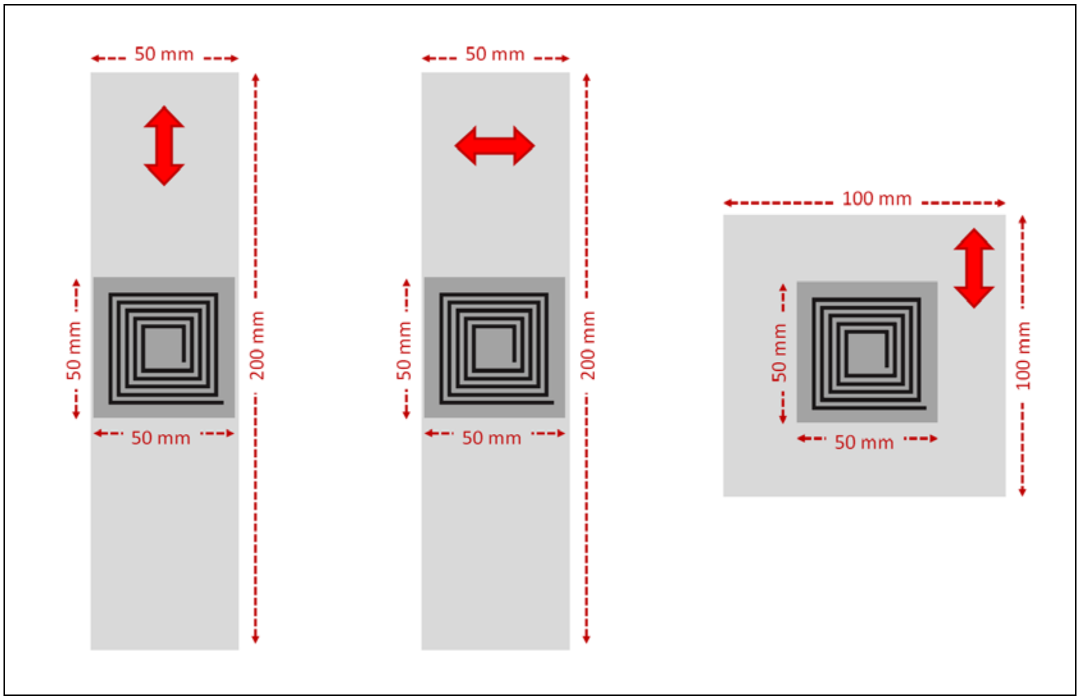


Figure 3- 4. Dimension of Fabric Specimens

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

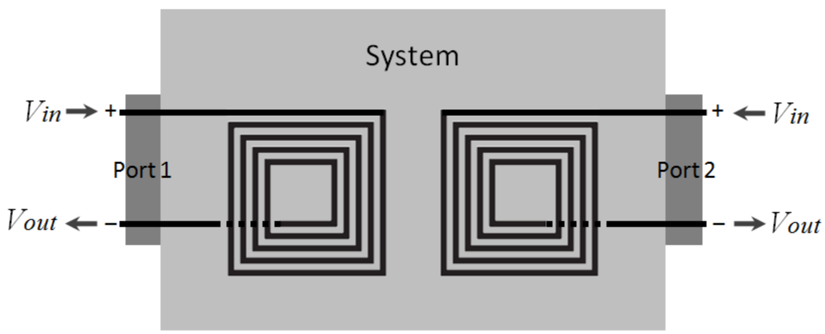
(Figure 3- 4). Identical antennas were produced with 6 to 12 replications for statistical analysis.

3.4.3. Transmission Performance

Known as S-parameters, scattering parameters are one of the most important characteristics of the antenna to explain the signal distribution within the wireless transmission system. It quantifies how RF energy propagates through a multi-port network. For an RF signal incident on one port, some fraction of the signal bounces back out of that port, some of it scatters and exits other ports, and some of it disappears as heat or even electromagnetic radiation. S-parameters would be complex in terms of magnitude and phase because those of the input signal are changed by the network. Often times, the magnitude is addressed only as it is of the most interest. As shown in Figure 3- 5, S-parameters refer to “voltage-out versus voltage-in” in the most basic sense.

S_{11} or S_{22} indicates reflection coefficient at each port. If S_{11} equals one, for example, the entire signal is reflected from the antenna and nothing is radiated or transferred. This highly depends on impedance matching at each port. The reflection coefficient has to be reduced to maximize the antenna performance. Return loss is generally defined as a logarithm form of reflection coefficient in dB as shown in Equation (5).

Transmission coefficient between two antennas, either S_{12} or S_{21}, indicates coupling which is the fractional amount of total flux linking the two coils. For example, if all the flux from the primary coil links the secondary coil, transmission coefficient equals one. Coupling is defined as a logarithm form of transmission coefficient in dB as shown in Equation (6). Measurement specifications for the transmission performance are listed in Table 3- 8.



$$S_{11} = \frac{V_{out\ @\ Port1}}{V_{in\ @\ Port1}} = \text{Reflection coefficient at Port 1}$$

$$S_{12} = \frac{V_{out\ @\ Port1}}{V_{in\ @\ Port2}} = \text{Transmission coefficient from Port 2 to Port 1}$$

$$S_{21} = \frac{V_{out\ @\ Port2}}{V_{in\ @\ Port1}} = \text{Transmission coefficient from Port 1 to Port 2}$$

$$S_{22} = \frac{V_{out\ @\ Port2}}{V_{in\ @\ Port2}} = \text{Reflection coefficient at Port 2}$$

Figure 3- 5. Two Port S-parameters

$$\text{Return Loss} = 10 \times \log_{10}(S_{11})^2 = 20 \times \log_{10}(S_{11}) \tag{5}$$

$$\text{Coupling} = 10 \times \log_{10}(S_{12})^2 = 20 \times \log_{10}(S_{12}) \tag{6}$$

Table 3- 8. Transmission Performance Measurements

Measurement	Abbrev.	Description	Unit
Return loss	S_{11}	Reflection coefficient	dB
Coupling	S_{12}	Transmission coefficient	dB

3.5. Statistical Analysis

Measurements of electrical and mechanical performance of different fabric antennas were analyzed with statistical models to see whether there is any statistically significant difference. For the first and second research questions, how silver ink performs with different fabric substrates and coating layers, two-way ANOVA model was established with interaction as follows. The effect of fabric substrates, coating materials, and their interactions were investigated. Tukeys method was used for post hoc analysis.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 \tag{7}$$

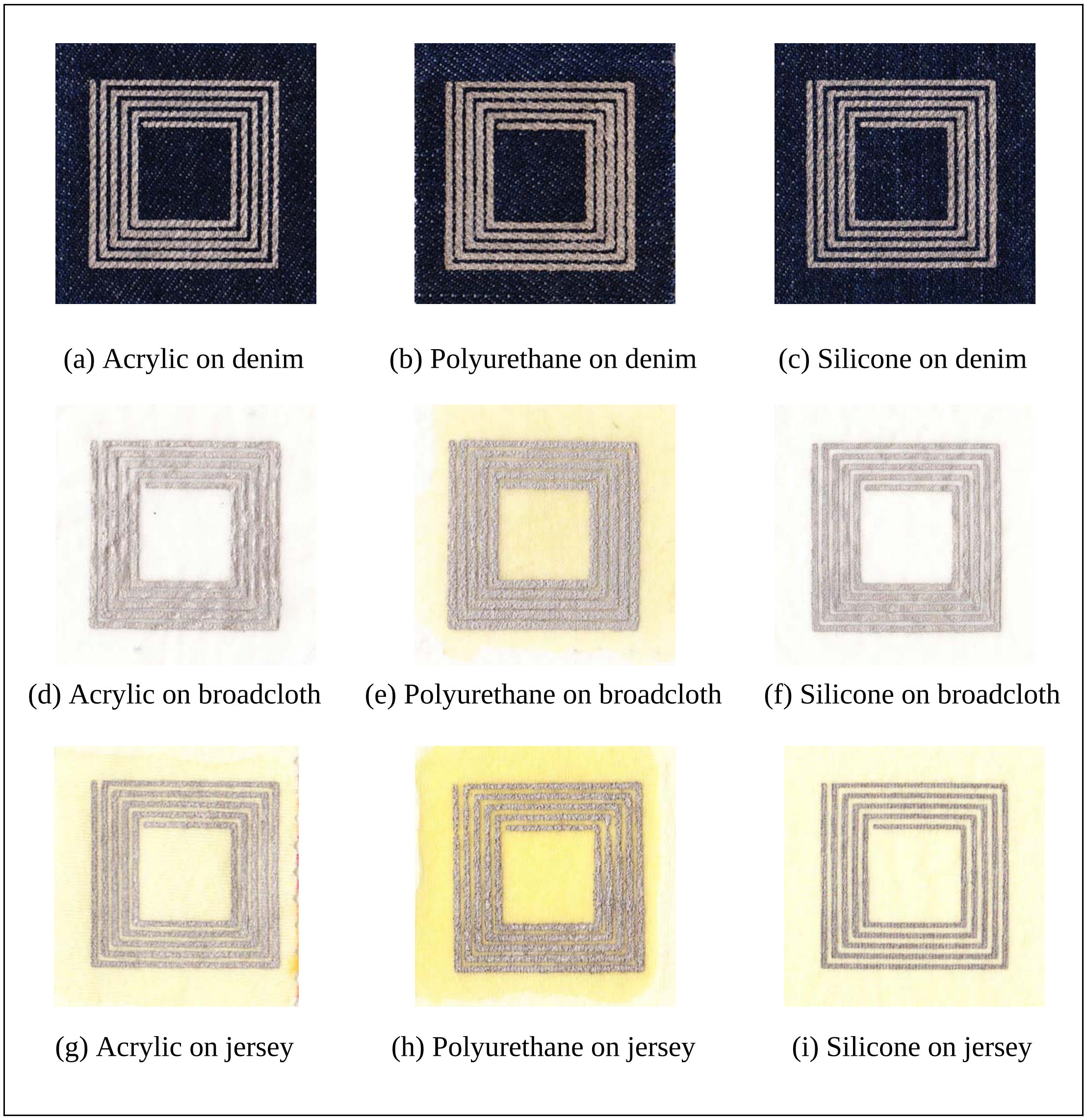
where, y = measurements, x_1 = type of fabric substrate, x_2 = type of coating material, x_3 = interaction between the fabric substrate and coating material, β_0 = intercept, and β_1, β_2, β_3 = coefficients

For the last research question, how physical conditions affect the wireless transmission, the relationship between scattering parameters and physical conditions of the antenna was analyzed. A linear regression model was adopted for each physical condition and given in Equation (8).

$$y = \beta_0 + \beta_1 x_1 \quad (8)$$

where, y = measurements, x_1 = physical conditions, and β_0 = intercept β_1, = regression coefficients

CHAPTER IV. RESULT & DISCUSSION



(a) Acrylic on denim (b) Polyurethane on denim (c) Silicone on denim

(d) Acrylic on broadcloth (e) Polyurethane on broadcloth (f) Silicone on broadcloth

(g) Acrylic on jersey (h) Polyurethane on jersey (i) Silicone on jersey

Figure 4- 1. Antennas Printed on Different Fabric Substrates and Coatings

Figure 4- 1 displays the appearance of printed antennas on different fabric substrates and coating materials. Silver ink was successfully deposited over the coated substrates. It had

clearest and sharpest edges on the silicone coating and slightly fuzzy texture on the polyurethane coating. Polyurethane-coated substrates became slightly yellowish on broadcloth and jersey due to the color of polyurethane.

4.1. Electrical Performance

Electrical performance of printed antennas was evaluated by measuring resistance and inductance. For an exact measurement, beginning and ending points on spiral line of the inductor antennas maintained open (not covered by protective coating) to secure the contact point with a probe. Low resistance and high inductance were observed when the conductive ink was printed on the fabric consistently and reliably.

4.1.1. Resistance

Resistance of fabric antennas was significantly different, not depending on fabric substrates but depending on coating materials. The reported resistances are the averages of the various coating materials (Table 4- 1) and various fabric substrates (Table 4- 2), respectively. Resistance on each fabric substrate and coating material can be found elsewhere (Appendix A). Tukeys post hoc analysis determined homogeneous subsets of the group. As shown in Table 4- 1 and Table 4- 2, there was significant difference on resistance only with polyurethane coating.

Table 4- 1. Resistance of the Antennas on Different Fabric Substrates

Fabric Type	Resistance (Ω)
Denim	100.23[a]
Jersey	114.94[a]
Broadcloth	122.42[a]

([a] refers to the homogeneous subset of the group)

Table 4- 2. Resistance of the Antennas with Different Coating Materials

Coating Type	Resistance (Ω)
Polyurethane	52.06[a]
Acrylic	137.85[b]
Silicone	158.78[b]

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

It was unexpectedly observed that resistance of the printed antennas increased dramatically after the protective coating was applied. Change of DC resistance before and after the protective coating was analyzed with repeated measure ANOVA. The results are reported in Table 4- 3 and Figure 4- 2. Polyurethane coating resulted in significantly low resistance compared to acrylic and silicone.

Table 4- 3. DC Resistance Before and After Coating (unit: Ω)

Measurement		Before coating	After coating	Difference (estimated)
Polyurethane	(n=23)	20.487[a]	61.709[a]	41.098[a]
Silicone	(n=24)	18.783[ab]	154.925[b]	86.854[ab]
Acrylic	(n=15)	15.053[b]	198.227[b]	106.640[b]

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

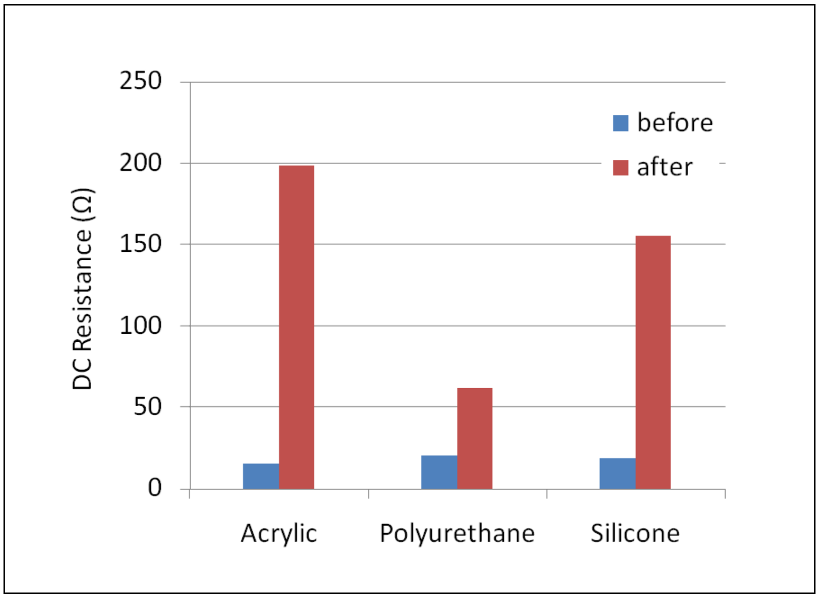


Figure 4- 2. DC Resistance Before and After Coating

The reason of resistance increase was due to the penetration of coating material throughout the conductive print layer. With the difference of degrees, each coating material was found on the back side of the fabric substrate even when the entire surface area was covered by silver ink. The silver ink was somewhat dissolved by xylene or acetone, which is included in the coating materials.

4.1.2. Inductance

Inductance of the printed antennas is reported in Table 4- 4 and Table 4- 5. The values are the average of the various coating materials (Table 4- 4) and fabric substrates (Table 4- 5), respectively. Details can be found elsewhere (Appendix B). Fabric substrate had the significant effect, while coating material had no effect on antenna inductance. Antennas printed on the broadcloth substrate provided significantly low inductance compared to denim and jersey. Polyurethane-coated antennas, which showed significantly low resistance, had slightly higher inductance than acrylic or silicone, but the difference was not significantly large enough.

Table 4- 4. Inductance of the Antennas on Different Fabric Substrates

Fabric Type	Inductance (nH)
Denim	905.31[a]
Jersey	922.46[a]
Broadcloth	624.37[b]

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

Table 4- 5. Inductance of the Antennas with Different Coating Materials

Coating Type	Inductance (nH)
Polyurethane	940.07[a]
Acrylic	785.84[a]
Silicone	764.63[a]

([a] refers to the homogeneous subset of the group)

Equation (9) is the typical model proposed to calculate the inductance (Meade & Delmar Learning, 2007). Factors that determine inductance value of inductors are number of turns (N), cross-sectional area of the coil (A), length of the coil (l), and relative permeability of the core (μ_r). Regarding that the shape of printed antennas was identical for all antennas, broadcloth antennas might have lower core relative permeability than other antennas as broadcloth fabric is the thinnest and lightest fabric substrate. Regardless of the weight or volume of fabric substrates, same amount of coating material (~0.05g/cm^2) was applied as a coating and this might result in comparably large amount of coating material left on the surface.

$$L = 12.57 \times 10^{-7} \times \frac{\mu_r N^2 A}{l} \tag{9}$$

where, L = inductance, μ_r = relative permeability, N = number of turns, A = cross-sectional area, l = length of coil, and 12.57×10^{-7} = absolute permeability of air

In addition, broadcloth is considered to have the most flat surface compared to other substrates due to its finest yarn count and plain weave type. The Equation (9) is extracted for perfectly flat surfaces which must be much different from the outside surface of fabric substrates. Unevenness of the surface may have an effect on inductance. Inductance of the antennas printed over the fabric substrates needs to be considered with a different model to include the effect of surface irregularity.

4.2. Mechanical Performance

For a reference, mechanical properties of the untreated fabrics were measured and reported in Table 4- 6. Untreated refers to bare fabrics where no antenna is printed and no coating is applied. As one of the thickest and heaviest fabrics, denim was the least extendible and the stiffest. Broadcloth was measured to be thinnest and least compressible. Representing the underwear fabrics, jersey was characterized to be the most flexible and light weight fabrics with the superior air permeability.

Table 4- 6. Mechanical Properties of the Untreated Fabrics

Measurement		Unit	Denim	Broadcloth	Jersey
E5	(warp)	%	0.0	0.0	2.7
	(weft)	%	0.0	0.1	5.0
E20	(warp)	%	0.3	0.5	11.4
	(weft)	%	0.1	1.5	19.5
E100	(warp)	%	3.2	1.9	17.6
	(weft)	%	1.2	6.6	21.5*
T2		mm	1.311	0.557	0.903
T100		mm	1.020	0.361	0.656
T2-T100		mm	0.291	0.195	0.247
Bending force		N	12.0	0.7	0.4
Weight		mg/cm^2	42.8	12.8	15.6
Air permeability		$cm^3/sec \cdot cm^2$	3.12	3.74	57.57

* 21.5% is the maximum measurement FAST system allows.

4.2.1. Tensile Property

Table 4- 7 and Figure 4- 3 shows the percent extension of fabric antennas in warp and weft directions at three different loads. After conductive printing and coating, tensile property

dramatically decreased, but still had considerable extensibility. Most of observed extensibility must have come from the untreated fabric region, not from the antenna area. The printed antenna area covered only 50% of entire fabric specimen as the actual specimen length fed in to the measurement was 100 mm out of the 200 mm (Figure 4- 4).

Table 4- 7. Extensibility of Fabric Antenna (%)

Fabric	Coating	E5 (warp)	E5 (weft)	E20 (warp)	E20 (weft)	E100 (warp)	E100 (weft)
Denim	None	0.000	0.000	0.317	0.067	3.217	1.150
	Acrylic	0.000	0.000	0.133	0.083	1.250	0.817
	Polyurethane	0.000	0.000	0.167	0.067	1.217	0.533
	Silicone	0.000	0.000	0.200	0.050	1.150	0.517
Broad-cloth	None	0.000	0.117	0.450	1.533	1.850	6.550
	Acrylic	0.330	0.000	0.150	0.267	1.017	3.083
	Polyurethane	0.000	0.050	0.133	0.483	0.700	2.817
	Silicone	0.000	0.033	0.100	0.367	0.533	2.267
Jersey	None	2.717	5.000	11.400	19.517	17.617	21.500
	Acrylic	0.467	0.183	4.317	7.017	10.483	21.017
	Polyurethane	0.367	0.800	3.300	6.317	7.733	18.983
	Silicone	0.417	0.767	2.450	4.200	7.017	12.750

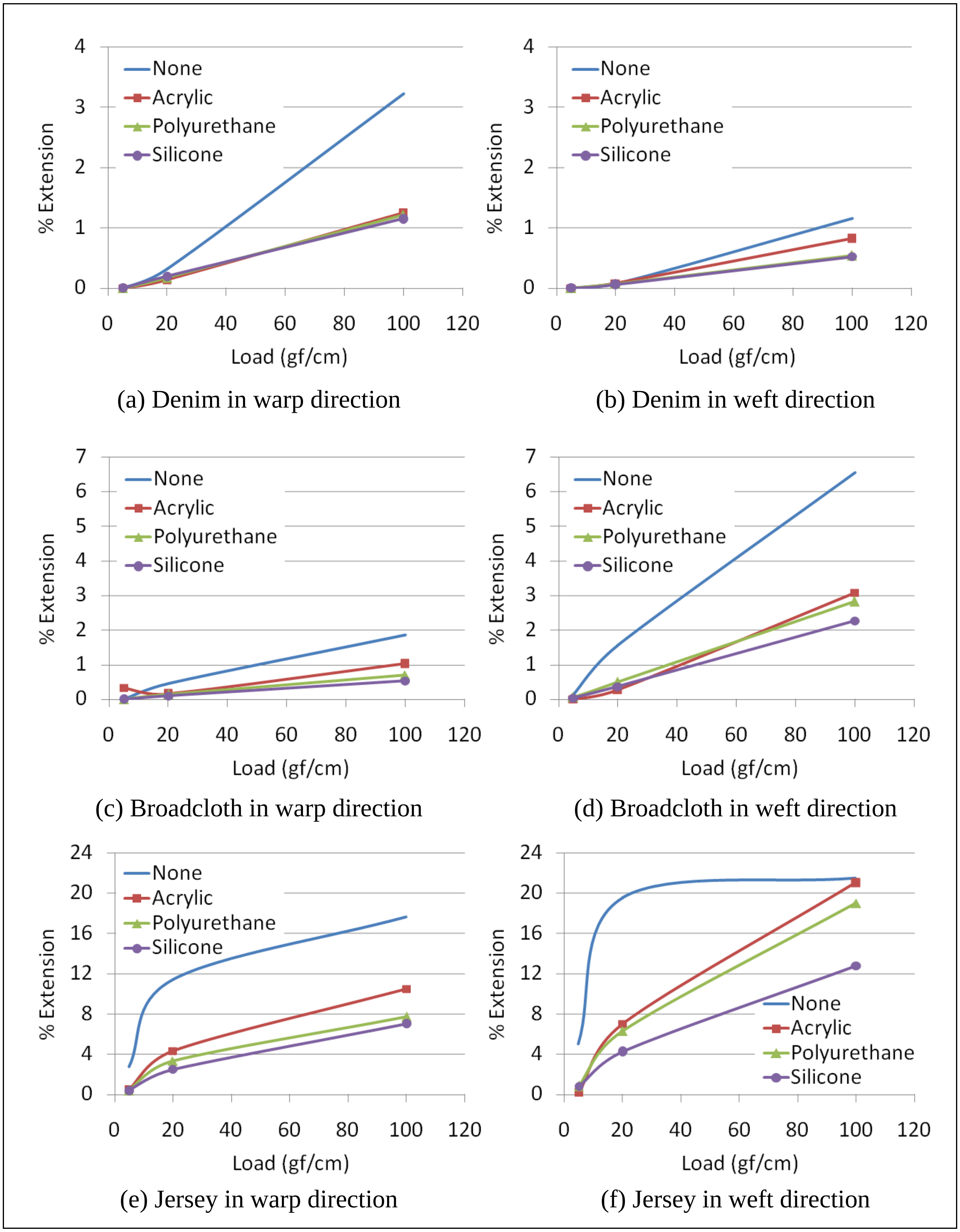


Figure 4- 3. Extensibility of Fabric Antenna

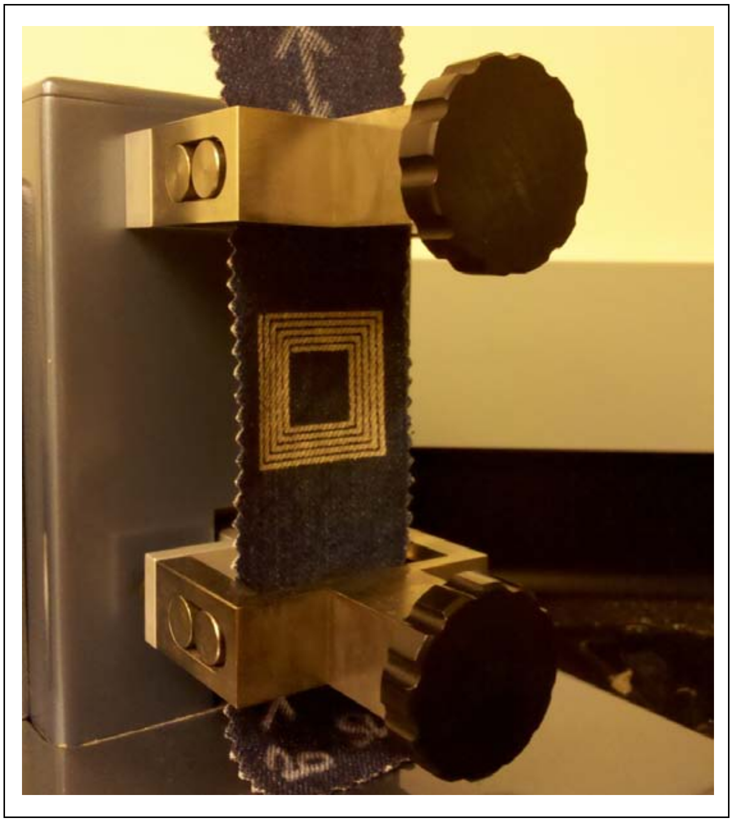


Figure 4- 4. Antenna Mounted for Extensibility Test

Table 4- 8. 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}

(^{a}, ^{b}, ^{c}, and ^{d} refer to the homogeneous subsets of the group)

ANOVA models verifying the effect of coating materials on antenna extensibility turned out very significant at 0.001 α-level. This significance was primarily due to the significant difference between treated and untreated fabrics (Table 4- 8). Lower level extension (E5) did not have any significant difference among coating materials, while the difference between silicone and acrylic coating became apparent with higher level extension (E20, E100).

Extensibility might not be very exactly measured, especially with acrylic-coated fabric antennas. Fabric substrates with low dimensional stability were observed to experience physical distortion after acrylic coating. The coated area was curved like a bow as acrylic underwent the changes of surface volume while being dried. The greatest extensibility of the acrylic-coated antennas might be due to this since the curvy portion must have been straightened by the force applied to extend the fabric.

4.2.2. Compression Property

Compression property is closely related to the fabric thickness as it is estimated by subtracting the thickness at 100 gf/cm^2 from the thickness at 2 gf/cm^2. Table 4- 9 describes those measurements by fabric substrates and by coating materials. Acrylic coating added about 1 mm to fabric thickness while polyurethane added about 0.3 mm. It was surprising that the thickness of the fabric decreased after the silicone coating. This seemed possible because the silicone made the fabric structure denser while it took its place between the yarns or even between the fibers pushing the airy space out of a fabric. As a result, compression decreased the most after the silicone coating (Figure 4- 5).

However, shown in Table 4- 10, statistical analysis proved that silicone coating did not decrease fabric thickness significantly ($p=0.650$), while polyurethane ($p=0.005$) and acrylic increased the thickness significantly ($p<0.001$). Compression seemed to be improved significantly after acrylic coating ($p<0.001$), which might not be true. As mentioned earlier, acrylic-coated antennas became physically distorted and this distortion affected the compression property. Printed antenna area covered 100% of tested area of compression test (Figure 4- 6).

Table 4- 9. Compression of Fabric Antenna (mm)

Fabric	Coating	T2	T100	T2-T100
Denim	None	1.3113	1.0203	0.2910
	Acrylic	2.2408	1.3938	0.8470
	Polyurethane	1.6395	1.2437	0.3958
	Silicone	1.1812	1.0558	0.1253
Broadcloth	None	0.5565	0.3612	0.1953
	Acrylic	1.6258	0.7908	0.8350
	Polyurethane	0.8337	0.6900	0.1437
	Silicone	0.5350	0.4347	0.1003
Jersey	None	0.9032	0.6560	0.2472
	Acrylic	2.0485	1.0250	1.0235
	Polyurethane	1.1662	0.9397	0.2265
	Silicone	0.7662	0.6702	0.0960

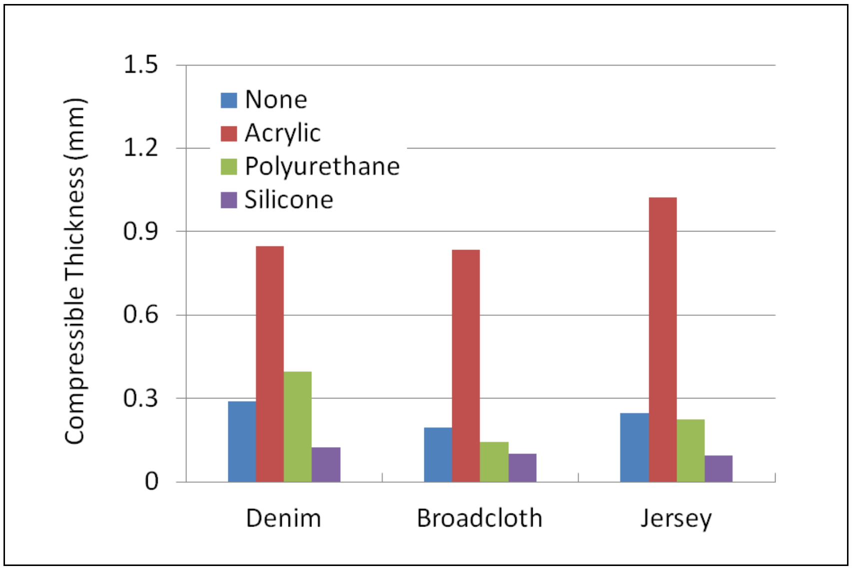


Figure 4- 5. Compression of Fabric Antenna

Table 4- 10. Effect of Coating Material on Antenna Compression (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]

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

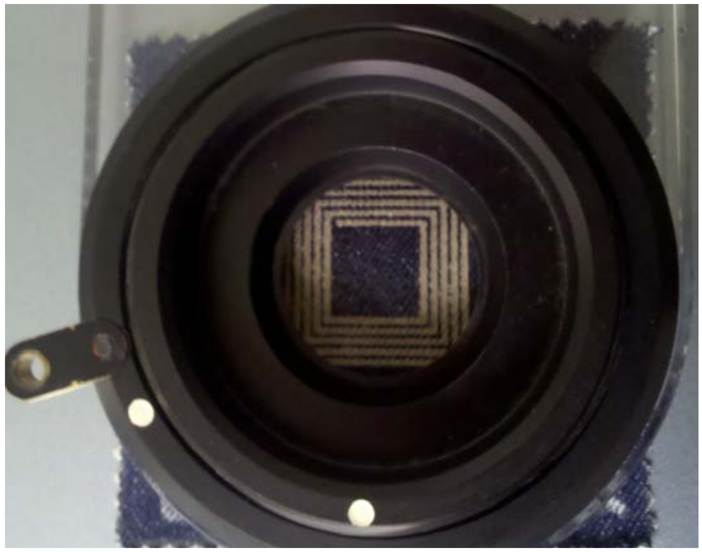


Figure 4- 6. Antenna Mounted for Compression Test

4.2.3. Bending Property

Bending seemed to be the property impaired most by printing the antenna. The bending force refers to the maximum force required to push the fabric specimen completely out of the instrument throughout the opening on the specimen support (Figure 4- 7). As instructed in ASTM D4032, bending force was measured from two-ply fabric specimens cut in 100mm × 100mm. Under the given dimension, the printed antenna region took 25% of fabric surface. If 100% antenna area was tested, unrealistic numbers of bending force must have been observed.

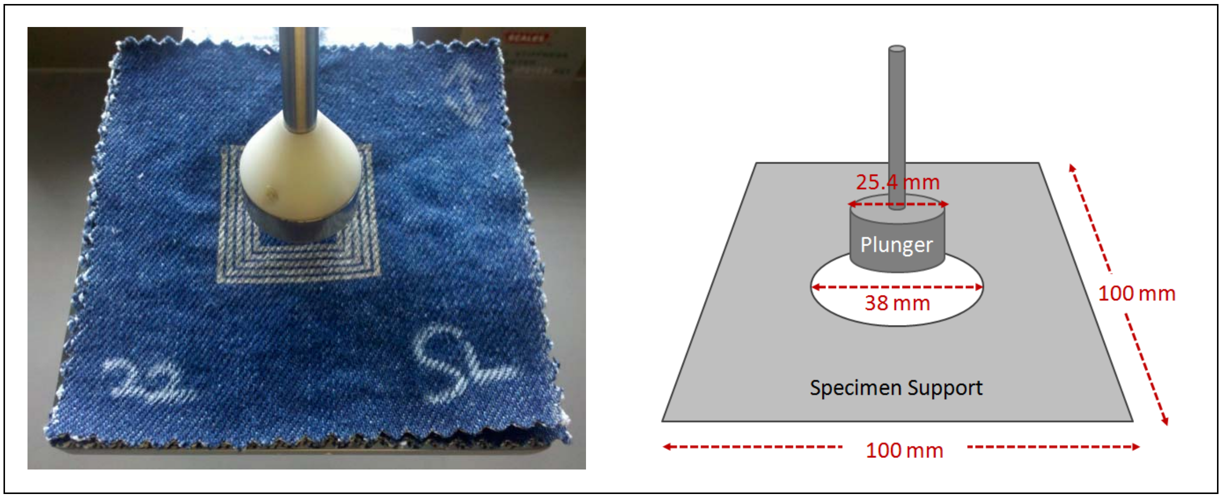


Figure 4- 7. Antenna Mounted on Fabric Stiffness Tester

Table 4- 11. Bending Force and Fabric Weight

Fabric	Coating	Bending Force (N)	Fabric Weight (mg/cm^2)
Denim	None	12.033	42.783
	Acrylic	130.583	51.717
	Polyurethane	233.283	54.600
	Silicone	76.750	51.317
Broadcloth	None	0.717	12.800
	Acrylic	28.633	19.600
	Polyurethane	46.867	22.083
	Silicone	11.583	18.100
Jersey	None	0.400	15.633
	Acrylic	21.650	23.717
	Polyurethane	67.633	26.867
	Silicone	12.683	23.133

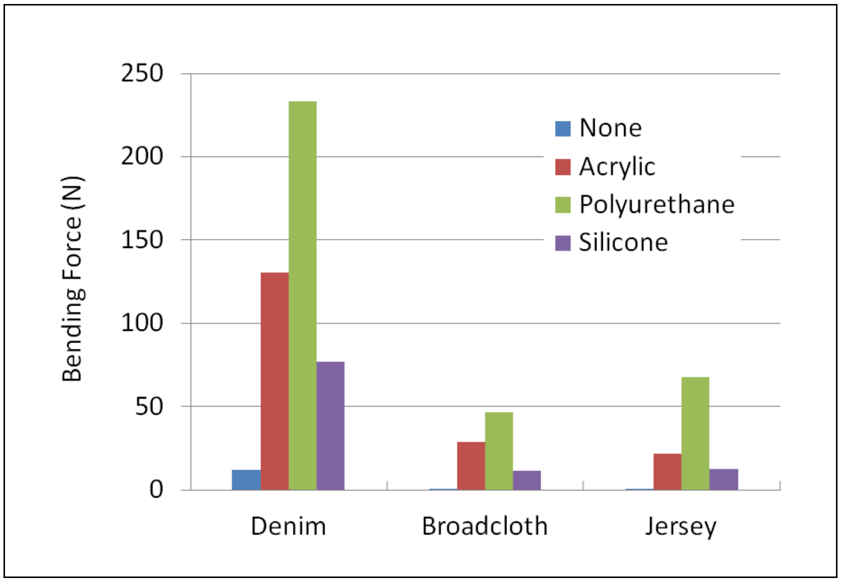


Figure 4- 8. Bending Property of Fabric Antenna

Change of bending property was very similar to change of fabric weight (Table 4- 11). They were considerably increased after the antenna was applied. Broadcloth and jersey antennas did not differ much from each other, while denim required huge bending force (Figure 4- 8). Especially, denim antennas coated with polyurethane had over 200 N.

Table 4- 12 shows how dramatically bending force and fabric weight increase. For both bending force and fabric weight, silicone had the least increase ($p<0.001$) and polyurethane had the most ($p<0.001$). This difference was very significant as much as the bending force became almost doubled for different coatings. For the weight-wise, polyurethane coating was observed to be the heaviest ($p<0.001$) and silicone was the lightest ($p<0.001$).

Table 4- 12. Effect of Coating Material on Bending Force and Fabric Weight

Coating Type	Bending force (N)	Fabric Weight (mg/cm^2)
Untreated	4.383[a]	23.739[a]
Silicone	33.672[b]	30.850[b]
Acrylic	60.289[c]	31.678[c]
Polyurethane	115.928[d]	34.517[d]

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

4.2.4. Air Permeability

The trends of air permeability changed alike to those of bending force and fabric weight. Air permeability greatly diminished after the antennas were printed (Table 4- 13). Broadcloth and jersey fabrics, which were originally much more permeable than denim, experienced more decease (Figure 4- 9). Polyurethane coating impaired the air permeability the most, while silicone coating impaired it the least. Fabric antennas still maintained considerable air permeability up to two third of the original air permeability on every fabric substrate.

Similar to extensibility, most of air permeability must have come from the bare fabric area, not from the antenna area, as the antenna area covered only 65% of the fabric specimen fed into the test (Figure 4- 10). However, the printed antennas were proven to have porous structure contributing to the entire air permeability to some extent as air permeability was different depending on coating materials. The level of extent could hardly be specified within the current scope of the research. Air permeability was reduced by approximately half to one third when the antenna system was applied to 65% of the surface area.

Table 4- 13. Air Permeability of Fabric Antenna

Fabric	Coating	Air permeability ($cm^3/sec\cdot cm^2$)
Denim	None	3.1250
	Acrylic	2.6933
	Polyurethane	1.4983
	Silicone	1.9583
Broadcloth	None	33.7400
	Acrylic	18.1033
	Polyurethane	15.6700
	Silicone	22.4533
Jersey	None	57.5733
	Acrylic	27.3667
	Polyurethane	20.7283
	Silicone	29.5233

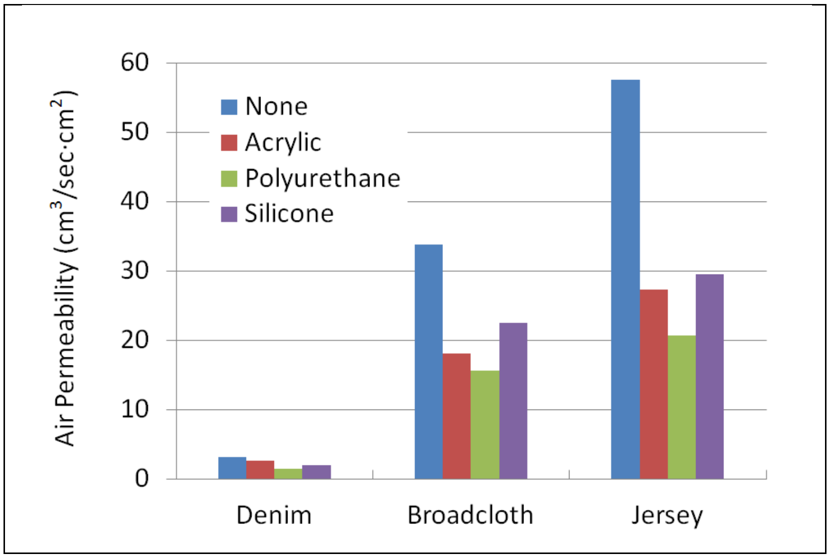


Figure 4- 9. Air Permeability of Fabric Antenna

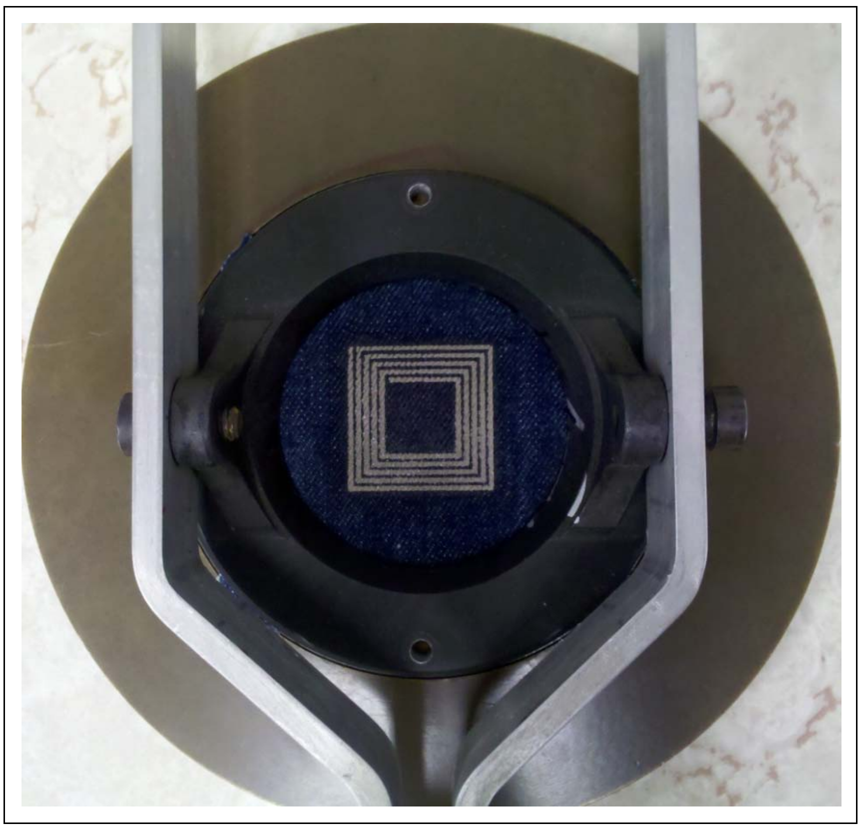


Figure 4- 10. Antenna Mounted for Air Permeability Test

Air permeability directly indicates thermal and moisture comfort of the fabric. At most times, thermal comfort is determined largely from the ability of fabric to discharge the heat and moisture rather than the ability to insulate them. Based on experimental results, silicone coating was found to be the most efficient to dissipate heat and moisture to the outer environment. Statistical analysis also verified that silicone-coated antennas were the most permeable ($p<0.001$), therefore, most comfortable. Polyurethane-coated antennas were less comfortable as they had the least air permeability ($p<0.001$). The difference was very significant between every coating material (Table 4- 14).

Table 4- 14. Effect of Coating Material on Air Permeability

Coating Type	Air permeability ($cm^3/sec \cdot cm^2$)
Untreated	31.4794^a
Silicone	17.9783^b
Acrylic	16.0544^c
Polyurethane	12.6322^d

(^{a}, ^{b}, ^{c} , and ^{d} refer to the homogeneous subsets of the group)

The experimental results showed that the selection of fabric substrates and coating materials needs to be optimized after considering mechanical and electrical performance. For example, silicone-coated antennas exhibited higher resistance compared to polyurethane-coated antennas, but mechanical performance of the silicone was far superior to any other coating materials. Especially, silicone-coated antennas had exceptionally low bending force and high air permeability, which contributes very much to comfort. The selection of fabric substrate may depend primarily on the end use purpose rather than antenna performance since three different fabric substrates take an inherent role in clothing application. Denim fabric, which was the most dimensionally reliable, had advantages that it could resist to physical distortion which might happen when the coating was fixed on the substrate surface.

4.3. Transmission Performance

In order to observe transmission performance, the spiral inductor was printed on denim fabric substrates and coated with silicone. Denim and silicone were selected as a fabric substrate and a coating material, respectively, because they have been proven to provide reasonable antenna function in terms of electrical and mechanical performance from previous experiments. Transmission performance of the fabric antennas were measured by observing reflection and coupling coefficient.

4.3.1. Return Loss

Return loss indicates the ratio of signals missed by being reflected from the antenna. Figure 4- 11 displays the return loss of 12 fabric antennas captured. Every antenna successfully resonated at 13.56 MHz with the average return loss of -17 dB (Table 4- 15). Considering that return loss less than -10 dB is generally regarded desirable (Gupta, 2008; Rajagopalan, 2008), the fabric antennas had considerably low return loss, which is beneficial to wireless transmission. In average, only 12.8% input signal was reflected by the fabric antenna.

Table 4- 15. Descriptive Statistics on Transmission Performance at 13.56 MHz

	N	Mean (dB)	Std. Dev. (dB)	Minimum (dB)	Maximum (dB)
Return Loss	12	-17.8204	1.9654	-20.0926	-13.8485
Coupling	12	-13.3454	2.2040	-18.8107	-10.7257

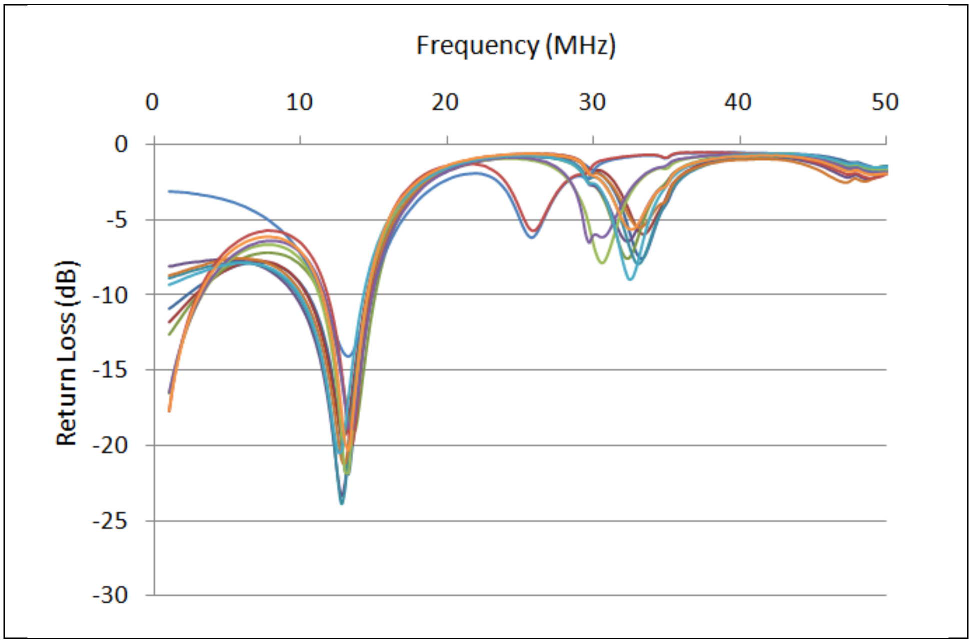


Figure 4- 11. Return Loss of Fabric Antennas

4.3.2. Coupling

Coupling is related to the self-inductance of each coil and the mutual inductance between them. Factors to influence the coupling include proximity, relative position of coils, core material, and how the coil is wound (Meade & Delmar Learning, 2007). Coupling was observed when one fabric antenna was put on the top of the other. As a result of the resonance at 13.56 MHz, coupling between two fabric antennas reached around -13.3454 dB at the target frequency (Table 4- 15 and Figure 4- 12). This meant that approximately 21.5% input signal was picked up by the other fabric antenna as a consequence of wireless transmission. According to Meade & Delmar Learning (2007), air-core coils often used in RF circuits typically have a coupling from 5% to 35% (equivalent to from -26 dB to -9 dB). Therefore, observed coupling was regarded appropriate for RF application.

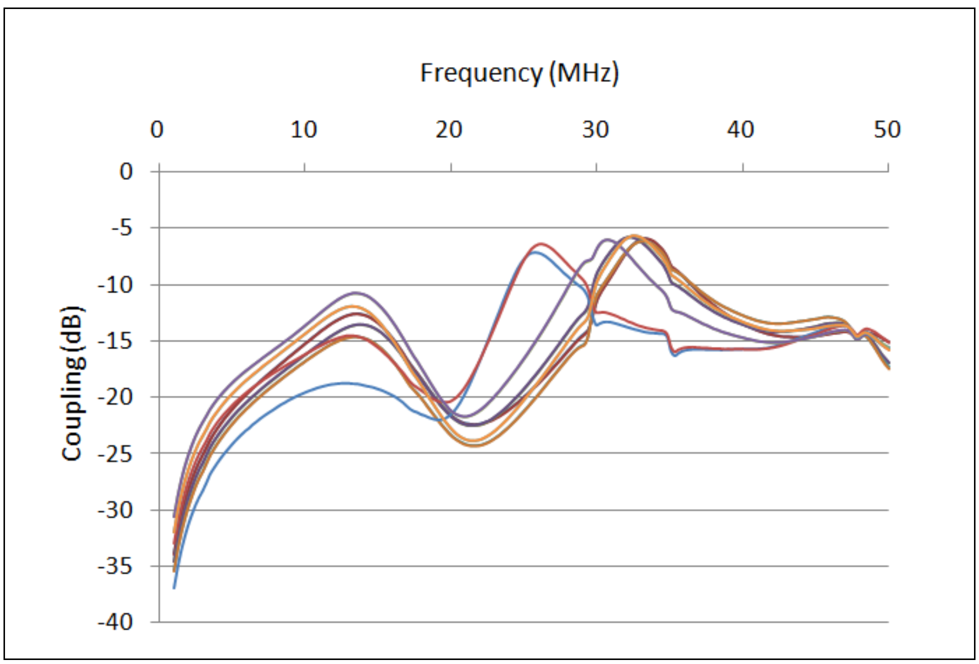


Figure 4- 12. Coupling of Fabric Antennas

4.3.3. Transmission with Distance

Having verified that the fabric antenna was suited to wireless transmission purpose, it was investigated how the distance between the antennas affected the transmission performance. Coupling was measured with five distance levels, which are 0, 0.63, 1.27, 2.54, and 5.18 cm, and explained statistically using a linear regression model. Change of return loss was not reported since the characteristics of a single antenna itself did not change with varying distance. As shown in Table 4- 16, coupling decreased as the distance got further and the fabric antennas did not function properly in more than ~ 2 cm distance.

Table 4- 16. Descriptive Statistics on Coupling with Distance

Distance (cm)	N	Mean (dB)	Std. Dev. (dB)	Minimum (dB)	Maximum (dB)
0	12	-13.3454	2.2040	-18.8107	-10.7257
0.63	12	-21.2769	2.4555	-25.6879	-18.4213
1.27	12	-23.8751	2.5317	-27.9870	-20.7547
2.54	12	-30.6066	2.6086	-34.2118	-27.7505
5.18	12	-38.8505	3.9284	-43.0121	-32.2355

A regression model developed to investigate the relationship between coupling and distance turned out very significant at 0.001 α-level (Table 4- 17). Figure 4- 13 displays the collected data sets and the trend line. Based on the trend line extracted, which was $y = -4.5593x - 16.819$, possible distance for wireless transmission could be estimated up to 2.0137 cm.

Table 4- 17. Regression Model on Coupling with Distance

	df	Sum of Squares	Mean Square	F	Sig.
Regression	1	4186.979	4186.979	338.459	.000*
Residual	58	717.502	12.371		
Total	59	4904.482			

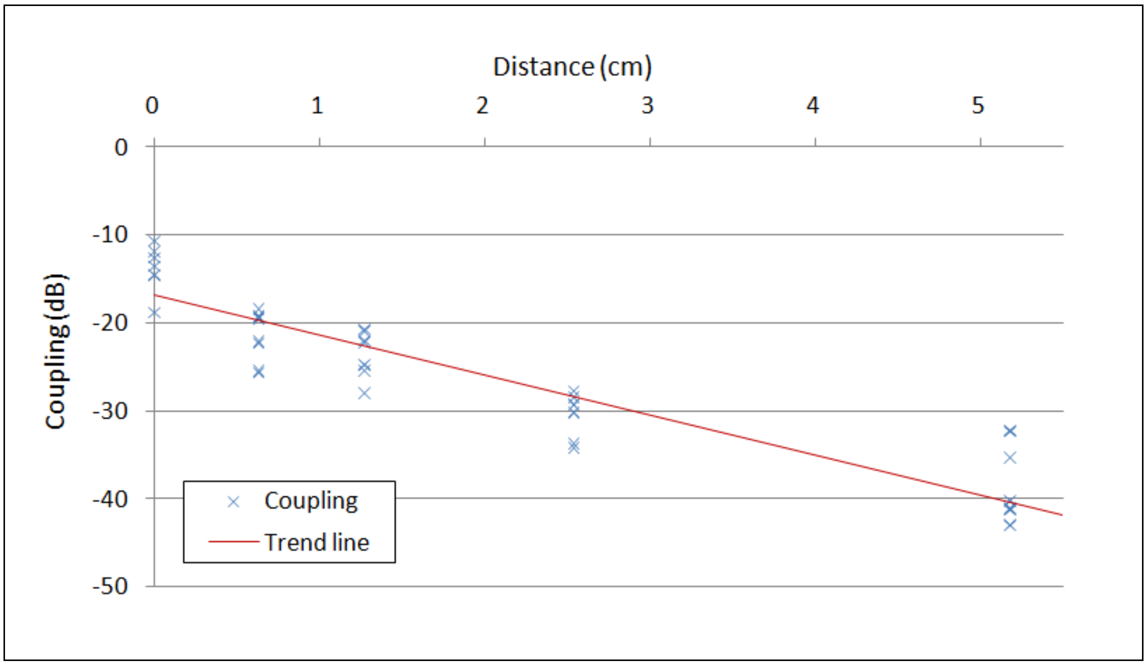


Figure 4- 13. Regression Model for Coupling with Distance

4.3.4. Transmission with Displacement

Transmission performance of the fabric antennas was also observed with displacement. Displacement simulates the situation in which one antenna layer shifts along the fabric surface of the other. Displacement is considered to occur within a multi-layered clothing system especially when the wear is in motion. The no gap was set between the layers while the antennas were dislocated from each other. Levels of displacement were kept 0, 0.63, 1.27, 2.54, and 5.18 cm, where zero displacement indicated that two antennas were laid exactly over the top of each other. Displacement level of 5.18 cm meant that antennas were completely separated by dislocating them since the dimension of inductor antenna was 3.5 cm × 3.5 cm. Change of return loss was not reported since the characteristics of a single antenna itself did not change with varying displacement. As described in Table 4- 18, coupling dramatically decreased as the antenna layers were dislocated and the antennas became not to function properly when they were dislocated by ~2 cm.

Table 4- 18. Descriptive Statistics on Coupling with Displacement

Distance (cm)	N	Mean (dB)	Std. Dev. (dB)	Minimum (dB)	Maximum (dB)
0	12	-13.3454	2.2040	-18.8107	-10.7257
0.63	12	-16.6029	2.6120	-21.4557	-13.6529
1.27	12	-19.8818	2.3325	-24.1149	-16.9794
2.54	12	-36.5304	6.7664	-48.6059	-29.1431
5.18	12	-38.1724	6.3747	-48.4528	-28.7904

A regression model was established to see the relationship between coupling and displacement statistically and the model was very significant at 0.001 α-level (Table 4- 19).

Figure 4- 14 displays the collected data sets and the trend line. Based on the trend line extracted, $y = -5.1611x - 14.977$, possible displacement between fabric antennas could be calculated up to 2.1358 cm for reliable wireless transmission.

Table 4- 19. Regression Model on Coupling with Displacement

	df	Sum of Squares	Mean Square	F	Sig.
Regression	1	5365.216	5365.216	138.845	.000*
Residual	58	2241.228	38.642		
Total	59	7606.444			

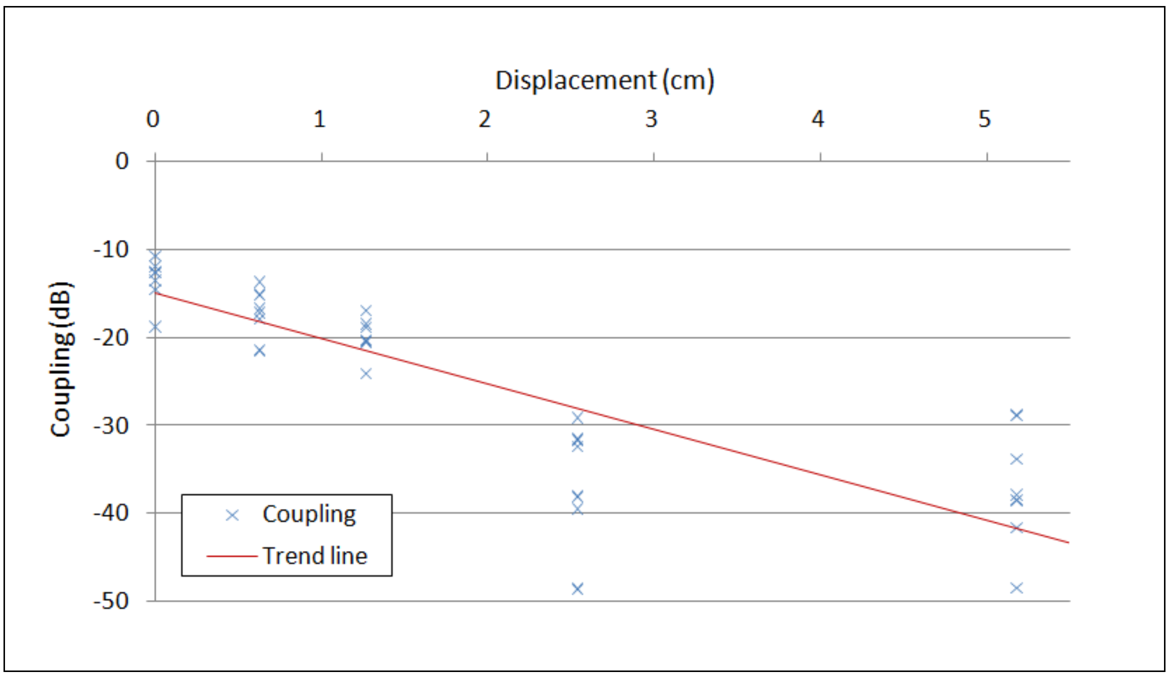


Figure 4- 14. Regression Model for Coupling with Displacement

4.3.5. Transmission with Stretching

For the next step, it was investigated if wireless transmission was valid when fabric antennas were extended by 5% and 10% of its original length, which was 100 mm. Extensibility is a very important characteristic of the fabric, which is much related to clothing comfort. A printed antenna has to withstand tensile deformation of the fabric substrate sustaining its performance. The reader layer and transponder layer were stretched at the same time while they were laid over the top of each other without any distance or displacement. Since there was possibility that electrical performance of a single antenna could change due to dimensional deformation, return loss was measured each time fabric antennas were stretched as well as coupling.

However, as seen in Table 4- 20, the regression showed no significant change on return loss at all ($p=0.885$). The performance of single antenna maintained in terms of signal reflection even though it was extended up to 10%. This might be because the area of printed antenna took only half of the fabric specimen. Thank to protective coating, printed antenna portion must have not been stretch very much. The return loss of stretched antennas hardly changed staying in the range of -10dB to -20 dB (Table 4- 21 and Figure 4- 15).

Table 4- 20. Regression Model on Return Loss with Stretching

	df	Sum of Squares	Mean Square	F	Sig.
Regression	1	0.215	0.215	0.022	0.885
Residual	16	159.166	9.948		
Total	17	159.381			

Table 4- 21. Descriptive Statistics on Return Loss with Stretching

Stretching (%)	N	Mean (dB)	Std. Dev. (dB)	Minimum (dB)	Maximum (dB)
0	6	-15.4706	3.2271	-19.0294	-10.3239
5	6	-15.6252	3.2653	-19.2581	-10.4154
10	6	-15.7381	3.2797	-19.1168	-10.6818

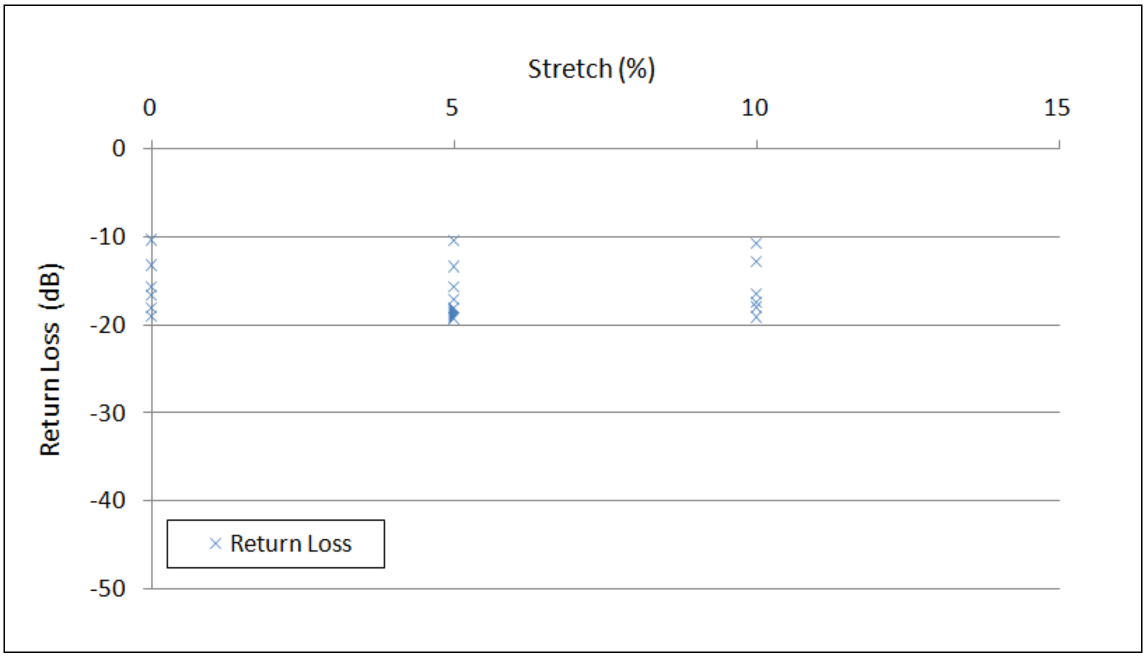


Figure 4- 15. Regression Model for Return Loss with Stretching

Coupling between two fabric antennas was also maintained successfully with 5% and 10% fabric extension. As analyzed in Table 4- 22, coupling was not significantly changed with stretched antennas (p=0.794). Extended by 10%, a fabric antenna still delivered about 20% of input signal to the other antenna (Table 4- 23 and Figure 4- 16).

Table 4- 22. Regression Model on Coupling with Stretching

	df	Sum of Squares	Mean Square	F	Sig.
Regression	1	0.334	0.334	0.070	0.794
Residual	16	76.140	4.759		
Total	17	76.474			

Table 4- 23. Descriptive Statistics on Coupling with Stretching

Stretching (%)	N	Mean (dB)	Std. Dev. (dB)	Minimum (dB)	Maximum (dB)
0	6	-14.3179	2.2784	-17.0570	-11.9358
5	6	-14.0901	2.3300	-16.9178	-11.7262
10	6	-13.9840	2.1460	-16.7539	-12.2194

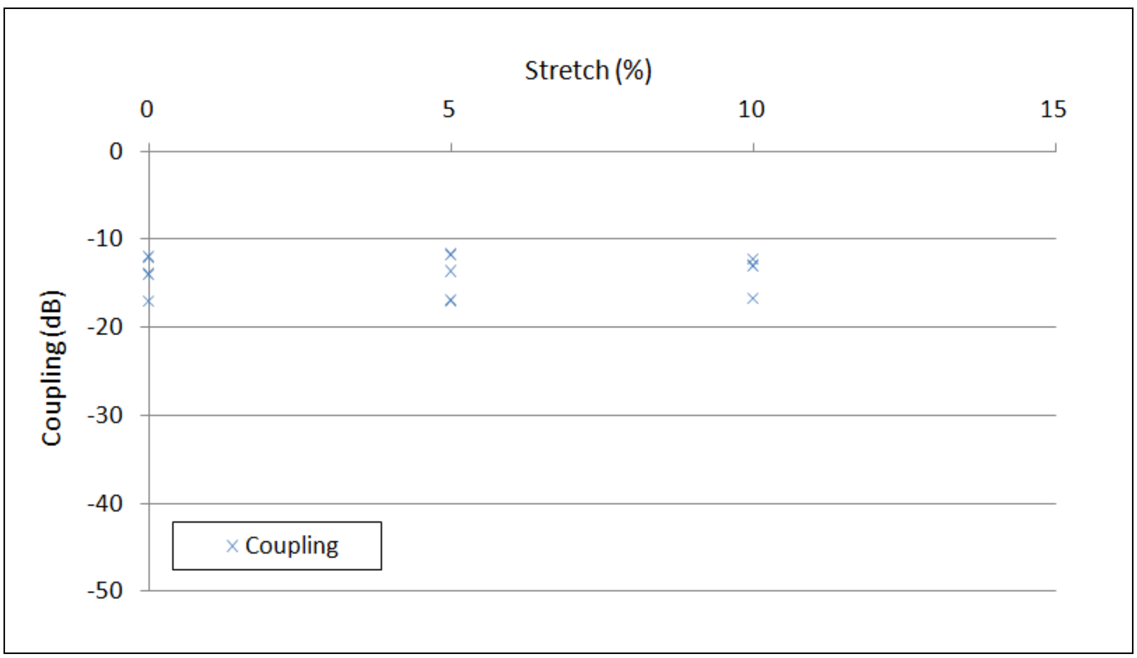
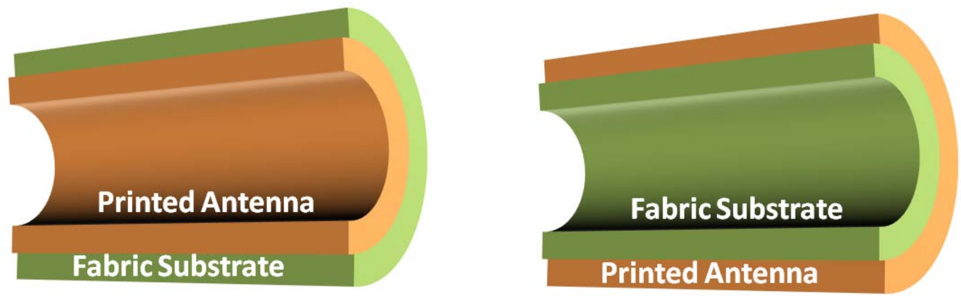


Figure 4- 16. Regression Model for Coupling with Stretching

Regarding that 10% was the maximum extensibility of the denim fabric made of 100% cotton, it did not have to take precautions to stretch fabric antennas if they are printed on denim substrates. As mentioned earlier, most of the stretch must have obtained from the bare fabric area rather than the antenna area which took only half of entire fabric specimen. Silicone protective coating is considered to prevent the deformation of printed antenna region.

4.3.6. Transmission with Bending

Bending direction has been divided into negative and positive deformation (Figure 4- 17) and analyzed separately as transmission performance of the fabric antennas showed much difference depending on bending direction. Negative curvatures (-0.25 and -0.50 K) were set for concave antenna surfaces and positive curvatures (+0.25 and +0.50 K) were set for convex antenna surfaces. The printed layer shrunk with the negative bending, while positive bending expanded the antenna. The reader layer and transponder layer were bent in the same direction while they were laid over the top of each other without any distance or displacement. Return loss of single bent antennas was observed as well as coupling since the antenna might change its electrical characteristics after modifying the shape.



(a) Negative bending (b) Positive bending

Figure 4- 17. Directions of Bending

As shown in Table 4- 24, negative bending did not change the return loss of fabric antennas significantly (p=0.284). Although the gap between return losses of several fabric antennas became larger as they got bent (Figure 4- 18), overall return loss retained around -16 dB regardless of the amount of curvature (Table 4- 25). Shrinking the printed structure did not affect the performance of single antenna at all.

Table 4- 24. Regression Model on Return Loss with Negative Bending

	df	Sum of Squares	Mean Square	F	Sig.
Regression	1	31.120	31.120	1.197	0.284
Residual	26	676.079	26.003		
Total	27	707.200			

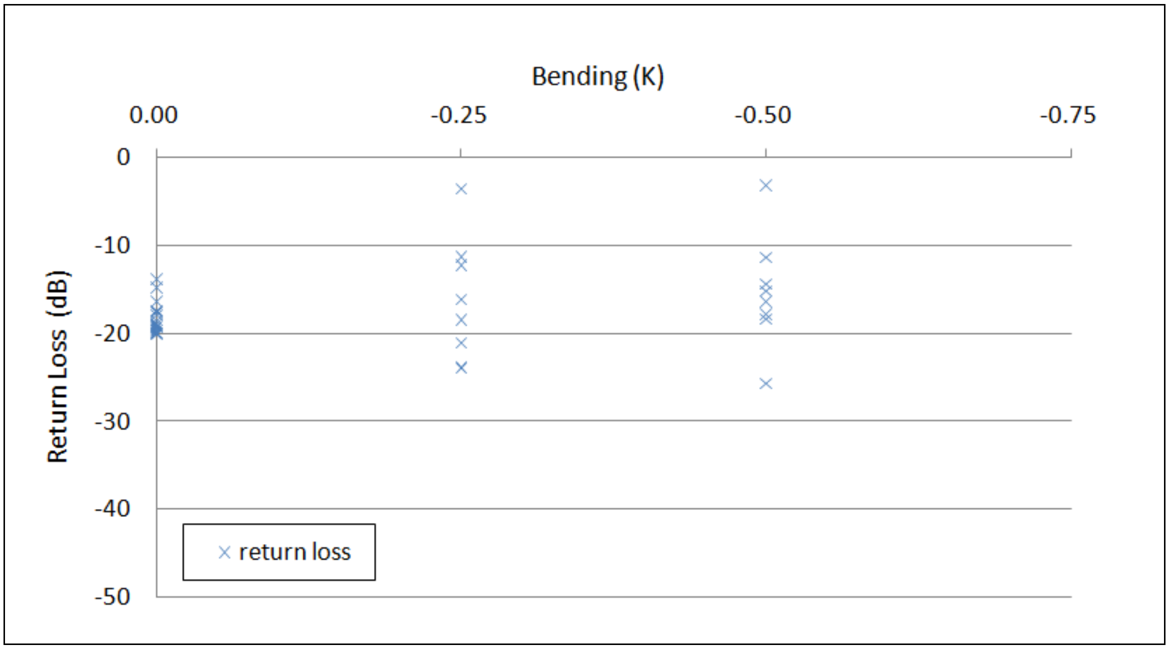


Figure 4- 18. Regression Model on Return Loss with Negative Bending

Table 4- 25. Descriptive Statistics on Return Loss with Negative Bending

Bending (K)	N	Mean (dB)	Std. Dev. (dB)	Minimum (dB)	Maximum (dB)
0	12	-17.8204	1.9654	-20.0926	-13.8485
-0.25	8	-16.3361	7.0249	-23.9320	-3.5939
-0.50	8	-15.3165	6.4125	-25.6983	-3.1979

From the coupling perspective, it seemed slightly decreased as bending curve was sharpened (Table 4- 26 and Figure 4- 19), but the change was not statistically significant (p=0.121) (Table 4- 27). Even after they were bent, most of antennas stayed similar range of coupling which was around -13 dB (Figure 4- 19). Wireless transmission remained possible even when the antennas curved in -0.5 K.

Table 4- 26. Descriptive Statistics on Coupling with Negative Bending

Bending (K)	N	Mean (dB)	Std. Dev. (dB)	Minimum (dB)	Maximum (dB)
0	12	-13.3454	2.2040	-18.8107	-10.7257
-0.25	8	-15.1615	7.0388	-26.4092	-9.6439
-0.50	8	-20.3828	16.3744	-47.1185	-9.8597

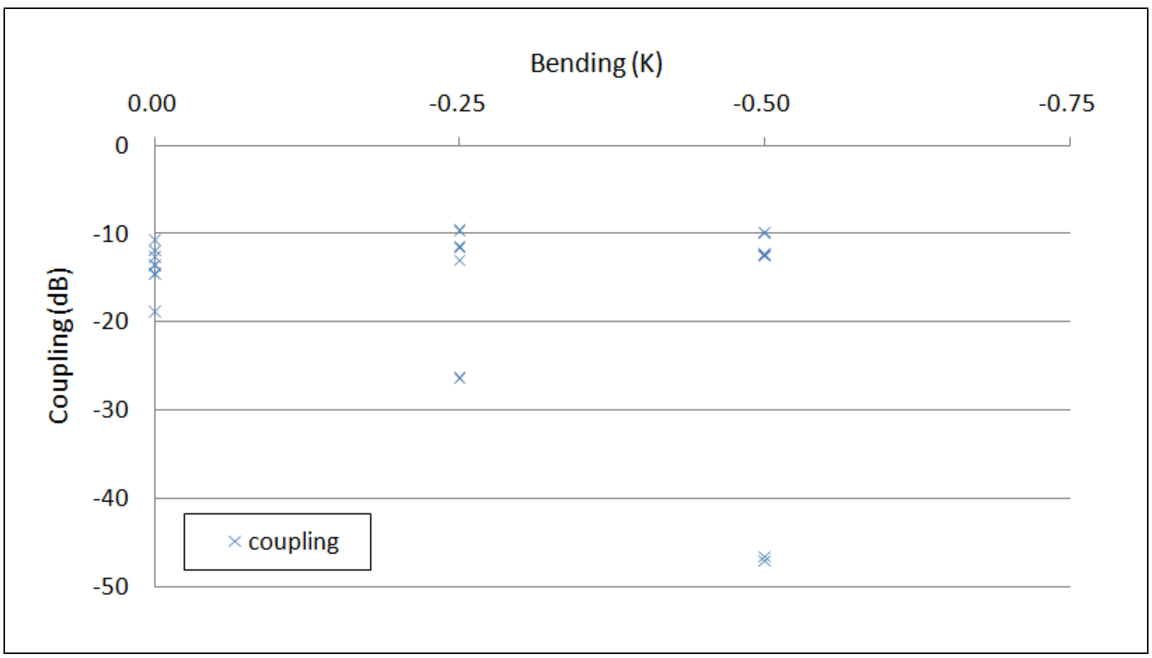


Figure 4- 19. Regression Model on Coupling with Negative Bending

Table 4- 27. Regression Model on Coupling with Negative Bending

	df	Sum of Squares	Mean Square	F	Sig.
Regression	1	227.052	227.052	2.574	0.121
Residual	26	2293.458	88.210		
Total	27	2520.509			

On the other hand, the effect of positive bending both on return loss and on coupling was very significant at 0.001 α-level (Table 4- 28 and Table 4- 29). Positive bending impaired return loss and coupling so much that wireless transmission was not possible even with the lower level curvature (Table 4- 30). Bending limits could be calculated using the trend lines extracted from collected data sets, $y = 23.05x - 17.115$ for return loss (Figure 4- 20) and $y = -45.789x - 15.066$ for coupling (Figure 4- 21). From the reflection point of view, possible bending was estimated to be 0.31 K, which was an equivalent curvature to a circle with ~3 cm radius. Bending limit was 0.24 K from the coupling perspective, which was an equivalent curvature to a circle with ~4 cm radius. These were considerably generous limits regarding the amount of curvatures for the narrowest body parts, such as wrists or wrinkles.

Table 4- 28. Regression Model on Return Loss with Positive Bending

	df	Sum of Squares	Mean Square	F	Sig.
Regression	1	645.162	645.162	24.490	.000
Residual	26	684.946	26.344		
Total	27	1330.108			

Table 4- 29. Regression Model on Coupling with Positive Bending

	df	Sum of Squares	Mean Square	F	Sig.
Regression	1	2545.947	2545.947	43.388	.000
Residual	26	1525.638	58.678		
Total	27	4071.585			

Table 4- 30. Descriptive Statistics on Transmission with Positive Bending

		Return Loss		Coupling	
Bending (K)	N	Mean (dB)	Std. Dev. (dB)	Mean (dB)	Std. Dev. (dB)
0	12	-17.8204	1.9654	-13.3454	2.2040
0.25	8	-9.2377	6.3975	-31.6756	9.6271
0.50	8	-6.6478	6.6037	-35.3797	8.6308

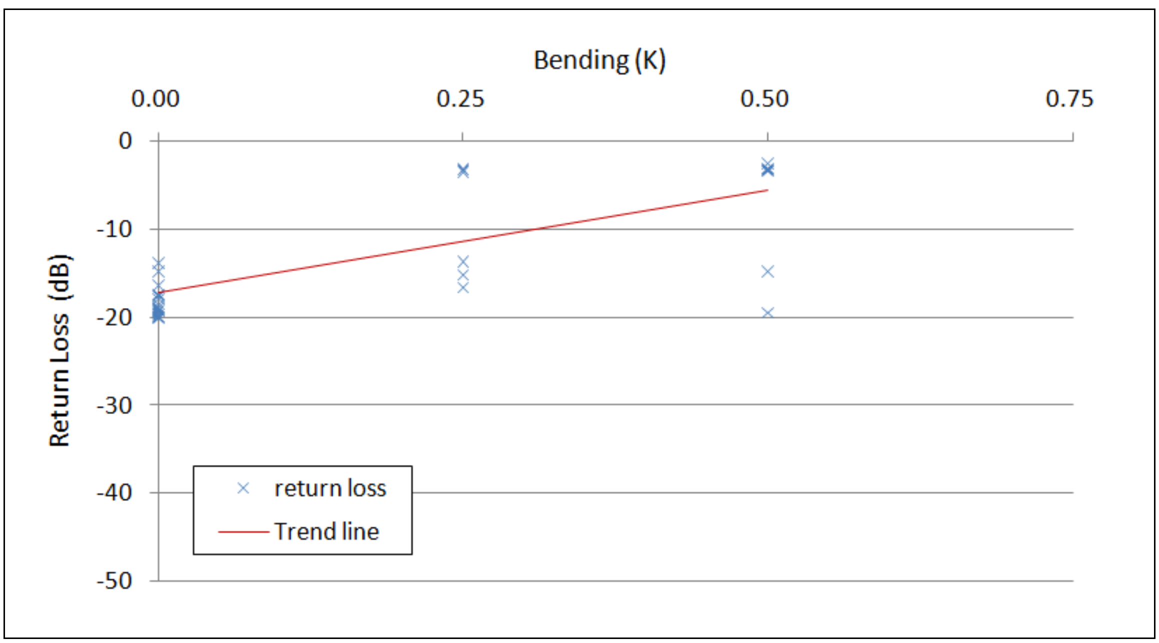


Figure 4- 20. Regression Model on Return Loss with Positive Bending

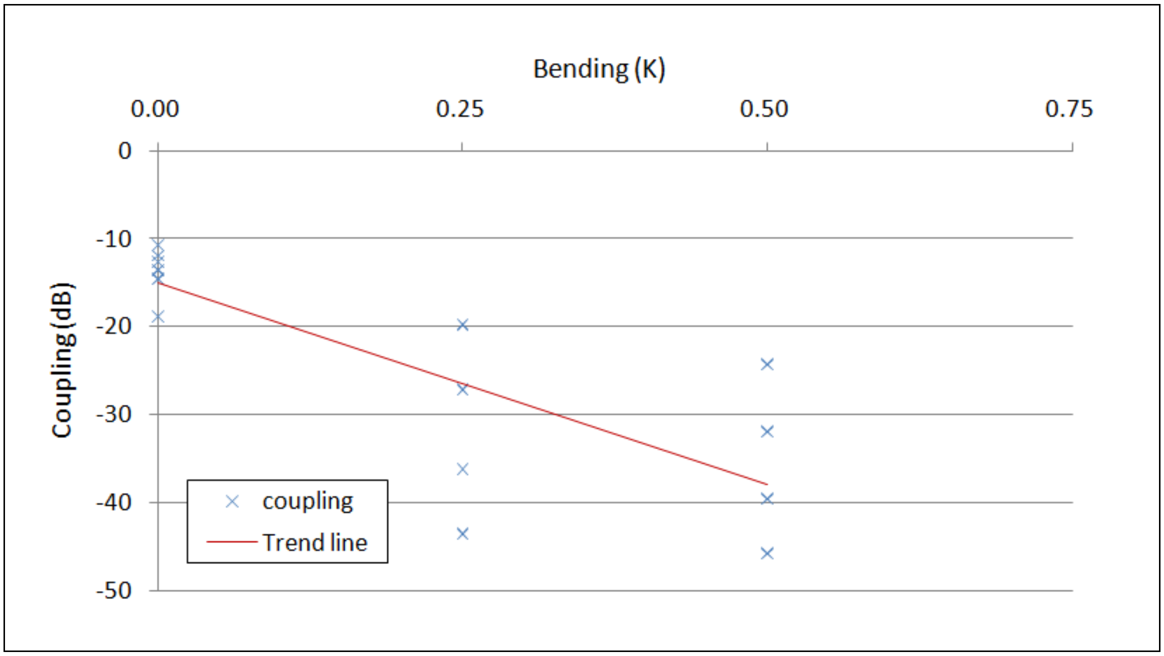


Figure 4- 21. Regression Model on Coupling with Positive Bending

Surely, the distinction between negative and positive bending came from the nature of deformation caused on the structure of antenna layer. Negative bending forced the antenna layer to shrink and this deformation did not have a significant effect on reflection and coupling performance. Positive bending expanded the antenna structure, specifically, more on its outer surface than the inner surface, and resulted in higher reflection and lower coupling. This was an interesting result since it implied the direction of fabric substrate on which the antenna can be printed. Antennas need to be printed in a way to induce negative bending rather than positive bending.

CHAPTER V. CONCLUSION & RECOMMENDATIONS

This research aimed to improve the wearability and furthermore the overall usability of smart clothing products. An inductor antenna was integrated into fabric surfaces to verify its potential for wireless transmission. Replacing the wired interfaces, the biggest merit of wireless system is the improved appearance appealing to users. In addition, wireless system would make it possible to link different fabric layers, which was previously unattainable with wires. Link between the layers enables to establish multi-layered smart clothing system performing various tasks at a different level.

Selection of fabric substrates became an important part of this research as everyday fabrics were chosen. Having more flat and smooth surfaces similar to paper, high density fabrics woven with fine synthetic filament yarns, such as nylon taffeta, take an advantage that they have few printability issues. Fabrics woven or knitted relatively loosely with staple yarns of natural fibers are much more challenging to print conductive media, but these are the fabrics most likely to be used for clothing in everyday life. Contrasting from previous investigations, in this research, practical fabrics, such as denim, broadcloth, and jersey, were used as a substrate. In order to print conductive media successfully, a surface coating had to be applied before conductive printing. Necessary structural layers were configured to be surface coating, conductive printing, and protective coating. Each layer provided the improvement of printability, conductivity, and protection of conductivity, respectively.

It was also meaningful that this research investigated the coating materials and focused on their effect on antenna performance. In previous research, a protective coating layer was applied after the conductive printing in order to secure the printed path, but emphasis was placed on conductive printing and not on coating. In this research, based on conformal coatings for conventional printed circuit boards (PCBs), acrylic, polyurethane, and silicone were selected and the effect of coating material was studied in terms of electrical and mechanical performance.

Relating to resistance measures, polyurethane coating had advantages, but the mechanical property of polyurethane-coated antennas was significantly inferior, especially in bending and air permeability. Mechanical performance of the printed antennas was outstanding when antennas were coated with silicone. Silicone-coated antennas were observed to be most flexible and air permeable, while polyurethane-coated ones were rigid and insulated. Acrylic was observed to be acceptable in terms of extensibility and compression, but in fact, acrylic coating had the most problems. Tensile and compression property could not be measured very exactly with acrylic-coated antennas. Acrylic underwent serious volume change on the surface when it was drying, which resulted in physical distortion of the fabric substrates. The problem became more serious when acrylic was coated over the jersey fabrics. Unwanted physical distortion of the fabric substrate contributed to the extensibility and compression.

One of the significant findings in this research was the effect of physical conditions in which the smart clothing would be situated during wearing. Basic dislocation or deformation such as distance, displacement, stretching, and bending was simulated while transmission performance of the fabric antennas was observed. Some critical points could be computed from the regression models established based on the relationship between physical conditions and transmission performance. In order to function properly, a fabric antenna required to be operated within ~2 cm distance. Considering that typical garment ease are 2.54 to 5.18 cm (1 to 2 inches) around the bust, waist, and hip circumference, this seems valid for clothing environment since multiple layers of clothing would not be far apart more than 2 cm in most of body parts under the typical wear conditions. Transmission performance was not impaired by stretching the fabric antennas, but impaired by bending them. Bending direction took important role. Negative bending was favorable to positive bending. This implies that antennas had better be printed on the backside of the fabric, which gets them bent concavely when worn.

This research has implications for smart clothing in the following ways. By getting rid of rigid and bulky wires from smart clothing products, wireless link possibly can increase the practicality of smart clothing. Primary markets of wireless link in smart clothing would be the healthcare sector. Smart sensors can capture the change of skin temperature or electrocardiogram in contact with skin. Buried deep in clothing, these sensors have to communicate with other devices such as a microprocessor and power source on the outside layers of the clothing. In this case, wireless transmission would be the only satisfactory solution to connect these sensors to outside world.

From the product design perspective, antennas had better be printed inside of fabric so that negative bending is induced rather than positive bending. This helps an antenna sustain its performance when it is worn. The region of collar, shoulder, waist belt, or cuffs is proposed to place the antennas, where stiffness is acceptable to some extent. Having different levels of accessibility and proximity to specific body parts, these locations could serve for various end-use functions. Outerwear or innerwear seems relatively easier to integrate the antennas as woven fabrics have higher dimensional stability compared to knit fabrics. For the underwear application, the upper chest area where the brand emblems are usually attached could be suggested. This is also a good place for monitoring vital signs as it is located near the heart. Protective coating is expected to function to preserve the fabric substrate from extreme deformations.

Suggested wireless system using inductively coupled antennas could fairly satisfy multi-dimensional usability of smart clothing products. Removal of wires out of clothing structure would improve the appearance and eliminate physical restrictions at the same time. Rather than any other material, silicone protective coating would provide the most comfortable clothing environment within the range to keep the antenna function at an optimal level. It would also enable the fabric antennas to resist against physical damages which possibly happen during wearing or maintenance situation.

Future research should focus on the following issues. Acrylic-coated antennas had grave consequences that physical deformation retained permanently such as cracks. They did not show any recovery from the deformation which resulted in discontinuity of conductive path, while polyurethane and silicone could take a role as a shock absorber. This must disqualify acrylic for proper protective materials. Unfortunately, this research did not extend its scope to durability of the antenna against the repeated mechanical deformation. It had been reported from the previous research that polyurethane protective coating could prolong the lifetime of conductive prints successfully (Cho, et al., 2007; Karaguzel, et al., 2009). Future research would include the study on durability of printed antenna depending on different coating materials. Attenuation of electrical performance after the repeated physical deformation is believed very important in durability research.

As another important variable affecting the mechanical performance of the fabric antenna, the portion of antenna area over the entire fabric surface could be of the interest for future research as well. In this research, the portion of printed antenna was different for each mechanical testing due to the dimensional difference between instruments: 50% for extensibility, 100% for compression and thickness, 25% for bending and weight, and 65% for air permeability. Since the printed antenna did not cover the entire surface of fabric specimen, fabric antennas could be considerably extensible, bendable, and air permeable. Fabrics partially covered by antennas are closer to realistic situations. The smaller the antenna is, the more comfort the antenna has. However, antenna cannot be as small as it can be since the antenna size matters to antenna performance. Placing the antenna on a proper location would be helpful to increase the comfort without reducing the antenna size.

The method to print conductive ink must be the most challenging when conductive printing is considered for mass production. Silk-screen process is one of traditional printing methods that are not very productive. Being a batch process, it causes much waste in time and material. Digital printing must provide a good solution in terms of productivity. Digital printing is also important in order to control the quality of print, which can never be overemphasized especially when printing electrical circuits on the fabric substrates.

In order to simulate the wearing situation more realistically, measurements may need to be extended to study the combinational effects of mechanical conditions, such as distance with dislocation or distance with bending. Also, the experiments can be designed to investigate the effect of thermal conditions on transmission performance as well as mechanical conditions. Especially, the presence of moisture near the fabric antenna is assumed to affect the antenna performance much. The worst case can be imaged that fabric substrates get wet when the wearer is sweating. Temperature is a good variable, too, since resistance is known to be very dependent on temperature.

The goal of this research was to verify the potential of wireless system in system approach in order to replace wired interfaces. The research was initiated to investigate the feasibility of inductive coupling for smart clothing application and it did indeed show great progress. Experimental results successfully answered the research questions proposed. Silver conductive ink performs differently according to different coating material. Silicone was suggested to support the antenna performance with mechanical performance impaired the least. Fabric substrates could be selected depending on different end-use applications because they did not affect the antenna performance significantly. Wireless transmission between fabric antennas was influenced much by the conditions in which they were situated. Based on the regression models, the limits of physical conditions that enable reliable wireless transmission were estimated up to 2 cm distance, 2 cm dislocation, and 0.3 K bending. These numbers imply that inductively coupled antennas have much potential for smart clothing application.

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APPENDICES

Appendix A. Resistance on Different Substrates and Coatings

Resistance on Different Substrates and Coatings (unit: Ω)

		Denim (n=17)	Broadcloth (n=27)	Jersey (n=18)
Acrylic	(n=15)	126.7	237.8	106.8
Polyurethane	(n=23)	40.8	44.2	65.6
Silicone	(n=24)	142.0	175.2	159.0

Appendix B. Inductance on Different Substrates and Coatings

Inductance on Different Substrates and Coatings (unit: nH)

		Denim (n=17)	Broadcloth (n=27)	Jersey (n=18)
Acrylic	(n=15)	780.2	464.7	918.8
Polyurethane	(n=23)	1064.2	706.6	1038.9
Silicone	(n=24)	829.8	581.7	828.9