Routing Methods Adapted to e-Textiles

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Abstract

Many small electronic devices such as PDAs and cell phones have changed our daily life over the past years. A next step will be the embedding of their functionality and circuits directly into textiles. In this paper we discuss for the first time, feasible methods and algorithms for establishing a routing structure in textiles while utilizing standard printed wiring board (PWB) tools. Our approaches focus on a woven textile with embedded copper wires, which guarantees usual wearing comfort, and circuits with few chips running at few megahertz. We present differences between regular PWBs and textiles regarding routing structure, space occupancy and electromagnetic compatibility (EMC) along with possible manufacturing methods.

Key words: e-textiles, routing, textile packaging, System-on-Textile, wearable electronics

1. Introduction

Today's society increasingly relies on ubiquitous computing. In daily life, instantaneous access to any kinds of information at any place is taken for granted. We are accompanied by many electronic devices such as cell phones, PDAs, notebooks and MP3 players, which are more or less bulky and not really wearable. Our vision behind wearable computing sketches future electronic systems to be an unobtrusively embedded integral part of our everyday outfit. Some attempts such as the Wearable Motherboard [1] and the WearARM [2] already exist. Nevertheless, they mainly consist of rigid or flexible printed circuit boards and hard boxes while their wearing comfort cannot compete with normal clothing. Among other factors, they lack drapability, which guarantees the typical textile-like feeling (some textile terms are briefly explained in section 2.1.).

Our approach, however, utilizes conductive fabrics for signal transmission. In this manner, conventional wires and entire circuit boards can be replaced by textile fabrics composing a System-on-Textile. Inspired from PWB manufacturing, we call the technology for electronic integration in fabrics *textile packaging* and the interconnection of electronic components on fabrics *textile routing*. Preceding to this paper, systematic investigations of the electrical performance of conductive textiles were already carried out by Cottet *et al.* [3].

A drapable embedding of electronics in clothing would enable new applications, e.g. in the medical field. The emerging field of medical prevention and rehabilitation necessitates continuous monitoring of patient's health condition by having sensing devices close to the body. The large area of clothing allows a distributed embedding of medical sensors and their preprocessing circuits. Additionally, clothing itself could accomplish sensor functionality [4] such as temperature and posture sensing. Wearable computing and thus, textile-embedded electronics ideally satisfies such requirements since clothing offers large areas, unobtrusiveness and body proximity. Other applications could be fashion or could lie in the typical wearable computing field of context awareness and social interruptability [5] where the wearable computer assumes the role of a personal assistant. There, sensors such as accelerometers, gyroscopes and microphones are embedded in clothing close to body joints. Based on sensors data and statistical methods, the personal assistant identifies context of the user and provides situation-dependent support.

To enable such functionality, research in textile packaging is of great importance. Since textile packaging is still in its infancy, we currently target modest goals compared to the current PWB technology. Our objective focuses on interconnecting few chips with few pads over a textile routing structure and utilizing them at locations where they can take clear advantages over PWBs. A typical example of a System-on-Textile is an application with many decentralized, small electronic circuitries such as in context recognition tasks.

2. Wiring Layer and Textile Substrates

In this section, we discuss the existing approaches and materials, which enable textiles to conduct electrical current. For better understanding, some textile-specific terms are first explained in the following subsection.

2.1. Textile Terms

- *Hand property or handle:* It is the way a fabric feels and thus, a very subjective judgement. The hand property may be crisp, soft, drapable, smooth, springy, stiff, cool, warm, rough, hard, limp, soapy, etc. Manufacturing processes and garment wash affects the final hand property of a fabric.
- *Drapability:* A term to describe the way a fabric falls while it hangs. It is the suppleness and ability of a fabric to form graceful configurations.
- *Warp and weft:* Weaving is the interlacing of warp and filling (weft) yarns perpendicular to each other. Warp yarns generally are subjected to more strain in the weaving process and therefore require more strength.
- *Tex:* unit of weight used to measure the density of fabrics. $1tex = 1g/1000m = 10^{-6}kg/m$

2.2. Textile Survey

Numerous electrically conductive fabrics already exist on the market. Generally, they consist of a non-conductive fabric as substrate and a metal or carbon structure as conductive component. The bigger the amount of metal in such a fabric composite is, the higher are the losses of the typical textile properties such as drapability and hand property. Besides, conductive polymers are still unsuitable for wiring because of their bad conductivity and their molecular instability. The non-conductive fabric usually consists of polyester or polyamide yarns whereas the conductive component ideally utilizes a good conductor such as silver and copper. In contrast to PWBs, substrate and conductive layer do not need to be spatially strictly separated in fabrics. They can be embedded into each other.

In the following, the structure of the conductive fabrics, i.e. woven, non-woven or knitted, is irrelevant to the discussed approaches.

1. *Fabric made of conductive yarn.* The fabric is entirely or partially equiped with this yarn. For this type of fabric, conductive layer and substrate are embedded into each other and the polymer yarn of the substrate forms the carrier frame for the conductive layer. Conductivity of a yarn can be established with different methods:

    (a) *Thin metal wire:* the metal wire is treated as separate yarn. The fabric composes of alternating polymer yarn and metal yarn. Additionally, the metal wire itself possesses a thin polymer coating for electrical insulation.

    (b) *Twisted metal wire:* Similar to 1a, but the metal wire is twisted around the polymer yarn. Therefore, they can be handled as single entity.

    (c) *Metal filaments:* the conductive yarn consists of staple yarn with metallic fibers.

    (d) *Metal coating:* the polymer yarn is chemically coated with a thin metal layer.

    Using this approach, no additional step after manufacturing of the fabric is required in order to establish conductivity.

2. *Plated fabric.* The non-conductive fabric is chemically processed after manufacturing in order to deposit a metallic layer. After this process step, the fabric is area-wide conductive.
3. *Printing on fabric.* A conductive structure is deposited (e.g. by ink-jet or screen-printing) on the non-conductive fabric.
4. *Sewing on fabric.* The conductive structure is sewed with conductive threads on the non-conductive fabric.

The main factor in the selection of conductive fabrics is the application. In order to establish diverse routing structures, at least two routing layers must be provided. Variant 1a emerges as most promising candidate for our purposes since it possesses several advantages over the other variants. Using variant

1a in woven form with insulated metal wires (the fabric consists of conductive threads in warp and weft direction crossing each other) already provides a layer-like structure due to the metal wire insulation. The insulation coating prevents short-circuits among the metal wires. Since the metal wire is treated as separate yarn, its location is more precisely defined than in variant 1b. These kinds of metal wires were originally developed by Elektro-Feindraht AG, Switzerland for clothing in shielding applications. Besides, they are robust against washing abrasion.

Variant 2 possesses several drawbacks. Firstly, the plating is limited to sub-micron thickness in order to preserve the typical textile properties. A bigger thickness would decrease the electrical resistance, but at the same time increase the probability of peeling. Several other factors such as corrosion and oxidation of the fiber surface and process-dependent partially plated fibers compromise reliable low-ohmic conductance. A routing structure could be introduced by etching whereby soaking of the etch liquid due to the capillary attraction in the yarn complicates a controlled fabrication process. Introduction of a second routing layer would need an additional plated textile sheet with a textile insulation layer between. This insulation layer must allow feedthroughs in order to interconnect the two conductive layers.

Printing of a conductive structure (variant 3) shows similar drawbacks as variant 2. Reliable conductance is difficult to achieve since most conductive inks and pastes base on silver filler resulting in a rather high brittleness. Bending of such a piece of fabric could immediately destroy its conductive structure. Deposition of an elastic polymer layer between the fabric and the conductive paste could mitigate this effect. Such a layer would smooth out the fabric surface and provide a better carrier for the conductive paste.

Finally, variant 4, sewing, must be treated specially: not a conductive layer, which must be structured in a later step, is added to the substrate, but the routing structure itself. It can only be manufactured in a serial process, i.e. the routing is composed of point-to-point connections, in contrast to the other variants where point-to-multipoint connections are feasible. Additionally, sewing with solid metal wires was proven as unreliable for electrical connections [6]. The mechanical stresses on the metal wires during the sewing are too high resulting in broken wires.

The remainder of this paper focuses on the fabric variant 1a as shown in Figure 1. It consists of a polyester multifilament yarn (4 threads and 15 filaments per threads, $8.4 Tex$) and coated copper wires woven by Sefar Inc. This fabric possesses a distance between each metal wire of $0.5mm$ (wire pitch) in warp and weft direction. The copper wire is $40\mu m$ in diameter; this with the $7\mu m$ insulation coating gives a final diameter $2r = 54\mu m$, which approximately corresponds to the thickness of a human hair. These dimensions represent a compromise between copper wire density, thus connectivity, and maintaining of textile properties.

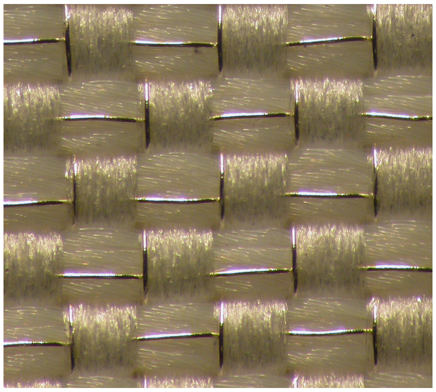


Figure 1: Woven conductive fabric prototype (variant 1a, wire pitch $d = 0.5mm$)

3. Textile Substrate Properties

This fabric type features significant differences to a standard printed wiring board (PWB) concerning mechanical as well as electrical properties. Table 1 gives a brief summary of these differences where the values for PWB and some values for the fabric were taken from literature. The following comments should give some clarification how the table needs to be interpreted.

The weight of the fabric can be estimated with formula (1) utilizing the tex value of the yarn and the yarn density where $n_l = 2$ because of warp and weft direction, $TEX = 8.4 \cdot 10^{-6} kg/m$, $n_{th} = 4$ because of the rep 4/4 arrangement (4 threads) and $d = 0.5mm$.

$$m = n_l \cdot TEX \frac{n_{th}}{d} \qquad [kg/m^2] \qquad (1)$$

For the weight of the PWB, a thickness of $0.3mm$ was assumed (corresponding to the fabric thickness) along with a specific weight of $1.8 g/cm^3$. Glass temperature T_g is much higher for polyester

Table 1: Property comparsion of substrates: PWB vs. fabric of figure 1

Property	PWB (FR4)	Fabric
hand property	rigid	smooth
weigth m $[g/m^2]$	540	140
glass temp. T_g $[^oC]$	135	220
CTE $[ppm/K]$	15	70
moisture abs. [%]	< 0.25	0.4
ten. strength $[MPa]$	275	60
ϵ_r	4.5	3.3
pitch $[\mu m]$	< 100	500
layout	arbitrary	grid, perp.
tolerance ($\pm$)	$30\mu m$	$40\mu m$, (8%)
# of layers	arbitrary	> 2
PWR/GND planes	yes	no

than for the PWB material. On the other hand, maximum operating temperature for polyester is limited to 150^oC. The coefficient of thermal expansion (CTE) of the polyester fabric cannot be determined precisely since the structure of the woven has a bigger influence on the geometry than temperature. The moisture absorbance neglects the capillary attraction caused by the woven structure. Relative permittivity ϵ_r is listed for polyester, however, fabrics are assembled of polyester fibers and air in-between and therefore, the effective ϵ_r will be smaller. While the layout on a PWB is of arbitrary structure, a layout in the given fabric must follow the perpendicular structure of the woven in the $0.5mm$ grid. Furthermore, trace width cannot be randomly chosen. It is bounded to the copper wire diameter and multiple of it when connected in parallel.

The layer count of a PWB is nowadays high and basically limited by technology and tolerances. In our case, it is not clear of how many layers the fabric consists. A definition of *layers to be spatially separated in vertical dimension and vias as interconnection between them* does not apply to the fabric since weaving does not allow spatial separation. Rather than this definition, many layers merges to one layer in our fabric due to the insulation of the copper wires. Traces crossing each other need to be on different layers in a PWB and vias must be used to switch layers. In the fabric, however, copper wires cross each other without shorts and no vias are necessary. On the other hand, warp and weft direction are strictly separate in the fabric. Figure 2 shows a cross section of such a woven fabric. In order to fulfill a direction change in the wire trace, an interconnection to a crossing wire is required. Further, traces can run on top of each other on different layers in a PWB. For fabrics, a complicated weaving technology is necessary to enable this option.

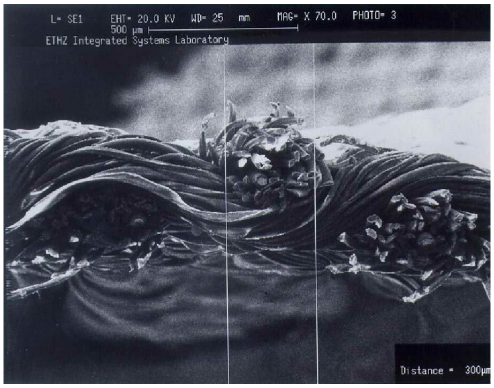


Figure 2: Cross section of woven fabric showing warp and weft

3.1. *Electrical Properties*

Similary to Cottet *et al.* in [3], we first wanted to know the most important electrical properties of the fabric, i.e. DC resistance R_s, characteristic impedance Z_0 (relative permittivity) and bandwidth bw. The measured parameters are shown in table 2. Note that the DC resistance is only about 1Ω higher than an unwoven straight wire of same diameter would have.

Table 2: Electrical properties of fabric

Property	Fabric
DC resistance $[\Omega/m]$	14.5
char. impedance $[\Omega]$	248
effective ϵ_r [-]	2.4
bandwidth [MHz/cm]	200

The DC resistance was measured using the 4-wire method. Considering a wire pitch of 0.5mm, we can convert this result in a sheet resistance of $7.3m\Omega/\Box$. In contrast, a PWB with $1oz$ copper $(35\mu m)$ possesses a sheet resistance of $0.49m\Omega/\Box$. Although, there is a factor of about 15 between the two values, power transmission in fabric without too many losses is possible by connecting several wires in parallel.

Permittivity was extracted from scattering parameter measurements of two wire pairs (signal

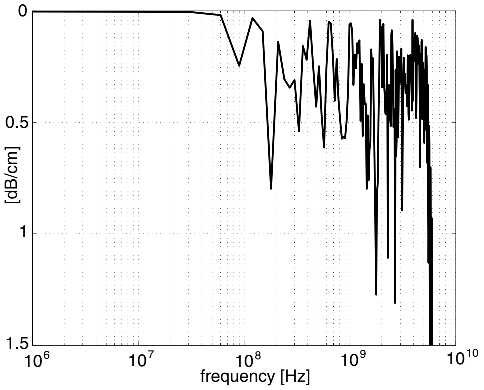


Figure 3: Bandwidth [dB/cm] for wire pair configuration in fabric

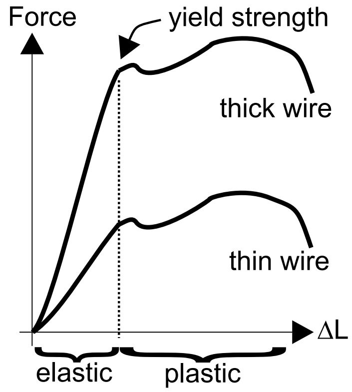


Figure 4: Yield strength of wires for elastic elongation

and ground) of different lengths using techniques explained by Grzyb *et al.* in [7]. Given the difference of lengths and the phase differences of s_{21} and s_{12}, respectively, phase per unit length can be extracted assuming linear phase. Eventually, effective permittivity ϵ_{eff} can be computed along with the characteristic impedance using formula (2) for wire pairs.

$$Z_0 = \frac{ln(d/r)}{\pi}\sqrt{\frac{\mu_0}{\epsilon_{eff}}} \tag{2}$$

Whereas ground planes in PWBs allow controlled impedances using microstrip configuration, they are not available in our fabric. Thus, we have to deploy wire pair configurations to control impedances such as described in Cottet *et al.* [3]. Nevertheless, it can easily be seen from (2) that the typical 50Ω-lines cannot be achieved with the low ϵ_r of fabrics. Even with several signal lines in parallel only about 100Ω line impedance can be reached as shown in [3].

The bandwidth can be computed similarly to the permittivity. Figure 3 shows that frequencies up to several 100MHz can be transmitted over short distances without big losses.

3.2. Mechanical Properties

The textile substrate has to withstand the mechanical stresses of daily life without damage. However, we also need to consider the occurring mechanical stresses during the weaving process. There, weaving stress mainly acts on the polyester yarn and on the copper wire, but not on the fabric as a whole. Since copper is stiffer and less ductile than the polyester yarn, it is the critical part for breaking. The force-strain diagram in figure 4 illustrates the maximal yield strength depending on the wire thickness. From this point of view, a thick wire would be beneficial for weaving. However, thickness has a big effect on the bending stress indicated by formula (3), where bending force F is proportional to the 4^{th} order of the wire diameter d. As result, wire thickness is limited by the required bending y during the weaving process on one hand and by the allowed load on the weaving machine on the other hand. Therefore, a thin wire would be favorable concerning bending forces. This tradeoff between strain forces and bending forces with respect to wire thickness was optimized by Sefar Inc.

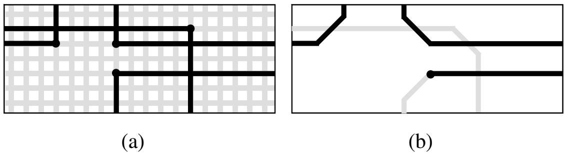
$$F \propto E \cdot d^4 \cdot y \tag{3}$$

Concerning the mechanical properties of the entire fabric, there exists many mechanical tests. A good overview of mechanical test for fabrics is given by Saville [8]. In the design of our fabric, we however focused on a secure embedding of the copper wires. We had to ensure that the woven substrate, i.e. the polyester yarn, absorbs strain stresses of daily life, but not the copper wires in order to avoid breaking of them. In other words, when applying the same force to the polyester yarn and the copper wire, the elongation of the copper wire ΔL_{Cu} must be bigger. Thus, the polyester yarn is the limiting factor. This statement is formulated in (4).

$$\Delta L_P \leqslant \Delta L_{Cu} \tag{4}$$

At this stage, we utilized the stress-strain diagram as simplified approach shown in formula (5) and neglect the effects of the woven structure. Applied to (4), we obtain (6) since force F and initial length L_0 are the same for copper and polyester.

$$\Delta L = \frac{F \cdot L_0}{A \cdot E_e} \tag{5}$$



(a) (b)

Figure 5: Textile routing (a) vs. PWB routing (b)

$$A_{Cu} \leqslant \frac{A_P \cdot E_{eP}}{E_{Cu}} \tag{6}$$

This formula needs to be translated to formula (7), so that we can use the tex unit and the so-called *inital modulus*, which is about $E_{Ptex} = 1000cN/tex$ for polyester. Eventually, we obtain $59\mu m$ as maximal diameter of the copper wire using the Young's modulus of copper $E_{Cu} = 125GPa$.

$$A_{Cu} \leqslant \frac{n_{th} \cdot E_{Ptex} \cdot TEX}{E_{Cu}} \tag{7}$$

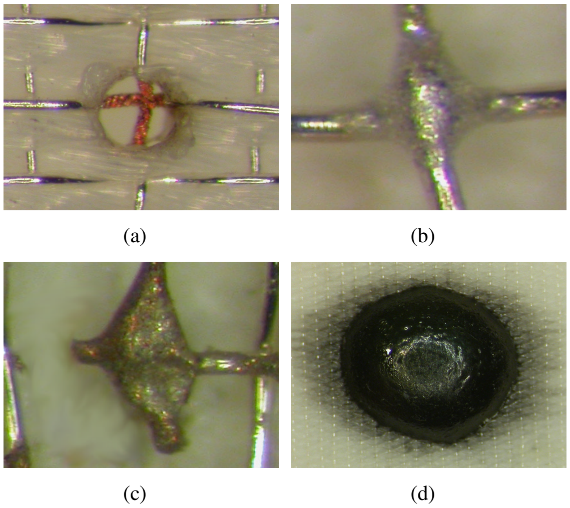
From mechanical point of view, a very small diameter for the copper wire would again be beneficial. However, electrical resistance increases with smaller diameter. To be on the safe side while still having reasonable electrical resistance, we chose a copper diameter of $40\mu m$. This diameter also conforms the requirements of the weaving process.

3.3. *Textile Properties*

A big difference between a flexible PWB and a piece of fabric concerning mechanical aspects is *drapability*. For example, a typical, flexible PWB can only be bent in one direction at a time while being stiff in the cross-direction. A textile farbic, however, can be bent in all directions at the time, which leads to a comfortable garment.

4. Textile Via/Pad Manufacturing

In this section, we briefly discuss the manufacturing technology for a routing structure in our fabrics. Considering the woven structure of the fabric, it is obvious that only perpendicular layouts can be implemented. Therefore, we cannot use the typical 45^o-bendings of a PWB layout when changing trace directions from horizontal to vertical and vice versa. This comparison is illustrated in figure 5, where the actual routing structure is emphasized in the wire grid (gray) and the polyester is omitted for ease. On the right side in the figure, the two layers of the PWB are shown in black and gray.



(a) (b) (c) (d)

Figure 6: Manufacturing process of a textile via; (a) Skinning, (b) Connecting, (c) Cutting, (d) Protecting

Secondly, the wires in the fabric are insulated against each other. Hence, the insulation needs to be removed at a point in order to interconnect crossing wires, which constitutes a sort of a via. Such a *textile via* is the fundamental building block for a routing structure in fabrics. The four necessary manufacturing steps for a textile via are depicted in figure 6.

1. *Coating removal on copper wires at defined intersections.* For example, laser ablation removes the coatings of the copper wires using standard laser machines for microvias manufacturing (6(a)).

2. *Interconnection of the skinned wire sections.* A small drop of conductive adhesive is dispensed on the ablated spot connecting the two crossing wires (6(b)).

3. *Cutting of certain wires in order to avoid short-circuits with the rest of the routing (since the wires span the entire woven area).* Cutting of the wires is achieved with laser light with a fluence greater than $4J/cm^2$ [9] (6(c)).

4. *Adding mechanical and electrical protection to interconnection.* Epoxy resin protection is deposited on the connection established (6(d)).

5. Textile Routing

After having shown that our fabric substrate as well as the embedded copper wires possesses promising properties for electrical signal transmission, we focus on the implementation of circuits on textiles. Firstly, we want to study the substrate area consumption of a circuit in comparison to a PWB. We then consider textile-specific constraints for placement and routing. Some of them might already be supported by EDA tools and some probably need new modifications, e.g. macros. Finally, we present two methods to solve the problem of cutting the shorting wires previously shown in figure 6(c). Our motivation is to utilize standard EDA tools with few modifications for textile substrates.

5.1. *Substrate Area Estimation*

To get a better understanding for dimensions, we compare the area occupied by a circuit realized on our fabric substrate and on a standard PWB. This comparison shows feasibility of routing structures on fabrics using empirical formulas summarized by Garg *et al.* [10] and by Brown [11] applied to the example stated below in italics.

Sensors nodes need to be embedded in clothing for context recognition purposes in wearable computing. These nodes are located at different body joints in a distributed manner and connected over textile transmission lines to a centralized processing unit forming a textile body area network (T-BoNe). Each sensor node consists of an accelerometer, a gyroscope, a magnetic field sensor and an analog-to-digital converter providing a serial interface to the T-BoNe. In this example, we compare space occupancy of a single sensor node implemented on the fabric substrate and on a PWB with 2 layers.

Table 3: Chip dimensions for sensor node

Chip	# of pads	Pad pitch [μm]	Chip area [mm^2]
Accel.	8	350	$(2 \times 3) = 6$
Gyroscope	32	350	$3.5^2 = 12.3$
Magn. sensor	16	250	$3^2 = 9$
ADC, 8 Ch.	24	250	$(4 \times 2.5) = 10$

Table 3 and table 4 summarize the given parameters. The pads are located along the chip side whose dimension is given first in column *Chip area* of table 3, except for the gyroscope where the pads are places around the entire chip die. Additional 1.8mm spacing was reserved on the substrate for each bonding row according to the rule of thumb by Brown [11] resulting in an extended footprint area A_{fp}. Core formulas for the estimation are given by (8) and (9) where L_W is the total wiring length, P_D the average chip pitch, N_T the number of terminals, A_W the total wiring area and N_L the number of layers.

Table 4: Substrate pitches

Substrate	Pitch P_W [μm]
PWB	150 (6mil)
Fabric	500

$$L_W = 2.25 \cdot P_D \cdot N_T \tag{8}$$

$$A_W = \frac{L_w \cdot P_W}{N_L} \tag{9}$$

The most important results are shown in table 5, where A_{tot} is the totally occupied area and A_{die} the sum of the bare die areas. Looking at their ratio, PWBs utilize their board area more then twice as efficient as the fabric. Although this result could have been expected in advance and might even become worse when other textile-specific factors such as higher tolerances and restricted routing capabilities are included, this drawback diminishes when considering the fact that textiles generally span a wide area, which can be utilized. Secondly, we target routing structures considering few chips with few pins running at low frequency as given in the example stated above.

Table 5: Area estimation for sensor node

	PWB	Fabric
$P_D[mm]$	6.6	6.7
$L_W[mm]$	1180	1211
$A_W[mm^2]$	89	303
$A_{fp}[mm^2]$	108	134
$A_{tot}[mm^2]$	197	437
$A_{die}/A_{tot}[\%]$	54	24

5.2. *Component Placement*

Among the usual constraints for a PWB such as having short connections and few vias, an important new

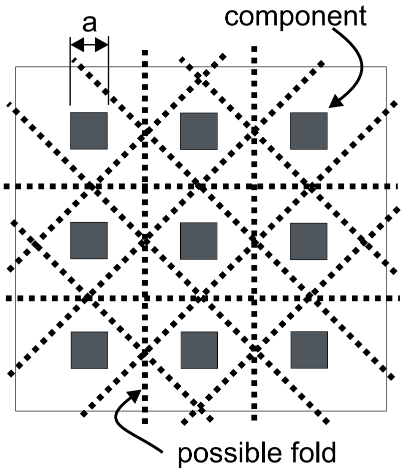


Figure 7: Placement of 9 components on a fabric, which ensures drapability

requirement is introduced for fabrics. Even though placement of electrical components on fabrics results in rigid spots, as much drapability as possible should be maintained. An approach is to place components and component groups, respectively, in a quadratic grid. Such a grid is shown in figure 7 for an example with 9 component groups. A maximum number of folds and folding directions can be achieved with such an arrangement while having components with minimal distances to each other. Eventually, best drapability is ensured. The components or component groups should be small and of equal size. The grid spacing is determined by the longest edge of a component group indicated with a in figure 7. Hence, the grid spacing would be at least $2a$. As result, a circuit with n^2 components placed in such a manner with n components in a row features $6(n-1)$ possible folds.

5.3. *Routing Layout*

As biggest contrast to PWBs, a textile layout must be entirely perpendicular determined by the structure of the woven fabric. Such a layout can be enforced by adjusting the design rules of the EDA tool or by the user. Favorably, different layers for horizontal and vertical traces are chosen in order to give a visual feedback. Secondly, a via must be placed at each change of trace direction while routing. At the same time, proper cuts need to be placed around the via avoiding shorts with other signals. For fast signals, the cuts should be as close to the via as possible in order to suppress signal reflections.

In a way, the cutting step in the textile routing process behaves inversely to the PWB routing process. While the electrical traces are already embedded in the fabric and connections must be removed by cuts, traces must be added for a PWB. Textile routing most probably resembles a vero board implementation. Below, four typical features of PWBs concerning routing are addressed and listed in comparison to the fabric.

- DC resistance of the thin copper wires in the fabric is rather high. Further, power/ground planes are not realizable in the fabrics. Therefore, several wires might be connected in parallel for power supply purposes. Reliability seems to be another reason to connect wires in parallel.
- Similarly, microstrip configuration is not feasible in the fabric and must be replaced by signal/ground wire pairs if applicable.
- Concerning pitch compatibility of fabric and components, an interposer can be utilized.
- Similarly to PWB fabrication where the number of drill holes mainly determine costs, it is the number of interconnects and cuts in a fabric forming a textile via, which dominates costs.

Following the philosophy of using as much functionality of the EDA tools as possible, we present two methods in the subsequent sections to integrate the additional cutting step (see figure 6(c)) in the existing EDA process.

5.4. *Method 1 for Cutting Step*

For the first approach, we need to define three types of thermal vias in the EDA tool including their 90^o turns as shown in figure 8. Each trench of a thermal via represents a cut in the textile whereas the drilling hole defines the electrical connection. Further, the definition of a power plane in the layer stack-up of the EDA tool is essential. Keeping the grid of the fabric in mind, the proper thermal via and its rotated versions must be chosen at each change of trace direction during the layout process in order to avoid unwanted connections to other nets. Pads need to be replaced by vias. Finally, only the gerber file of the power plane and of the drilling holes will be needed for manufacturing. The power plane file defines the cuts whereas the drilling defines the positions for the skinning, for the adhesive drops and for the protective epoxy. Figure 9 illustrates the first approach whereby the gray lines indicate the grid of copper wires.

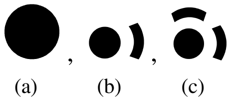


Figure 8: Three thermal via definitions in EDA tool for method 1

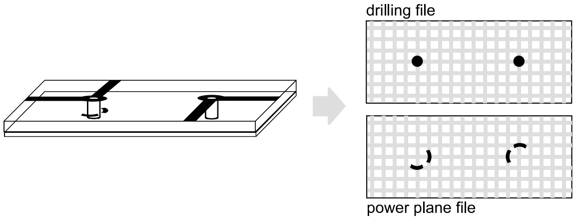


Figure 9: Necessary manufacturing layers for first method

5.5. *Method 2 for Cutting Step*

The second approach is similar to the first one, but no attention to the choice of vias must be paid and no power plane is necessary. It is based on the IPC-D-356A file generated by the EDA tool. This file contains all information about via/pad positions and the nets they belong. A script reads this file and generates a gerber file containing the positions and lengths of the cuts. This file together with the drilling file represents the manufacturing data as can be seen in figure 10.

The algorithm in the script goes through the list of vias and pads. It selects a via/pad and perpendicularly seeks in all four directions in the plane until it hits another via/pad, a cut or the border of the board. In case of a via/pad, the algorithm checks whether it belong to the same net. If not, a cut of appropriate length is placed at the appropriate location in order to electrically separate them. In case of a cut or the border, the selected via/pad is already insulated and nothing needs to be done. After that, the next via/pad in the list is selected and the algorithm is iterated again. The principle of this algorithm is shown in figure 11 where the arrows indicate the seek direction and the letters denote the electrical nets the via/pad belongs to. Figure 12 expresses the result with the added cuts after iterating over pad A.

Main goal of the second method is to preserve the mechanical strength of the textile. It analyzes the structure and places cuts only when necessary. In comparison, method one places cuts at all bendings of a signal path, which is not always needed. This drawback is, however, relieved when vias and pads are casted in epoxy later on. Nevertheless, approach one is rather error prone since the tool user has to choose the right vias for the cuts whereas the cuts are placed automatically in approach two. However, approach two produces open-ended traces in the electrical path leading to worse electrical performance, though this effect is not severe at low frequencies. Besides, the script for method two can easily be changed so that cuts are always placed similarly to approach one. It is implemented in MatLab and can be downloaded at http://www.ife.ee.ethz.ch/~ilocher/texrout/. This script has already been successfully used for several projects.

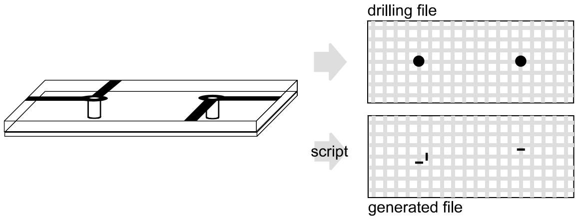


Figure 10: Necessary manufacturing layers for second method

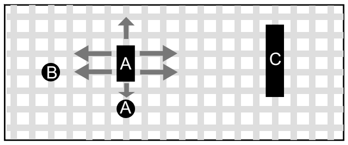


Figure 11: Principle of method 2 (arrows indicate seek directions, letter indicate nets)

5.6. *Constraint Summary*

A short overview of the additional routing constraints for EDA tools is summarized below.

- Placement of components in quadratic grid
- Ensure perpendicular routing
- Place via at each trace direction change
- No ground/power plane available

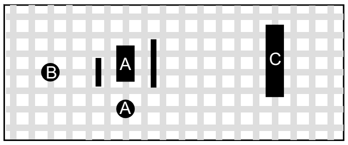
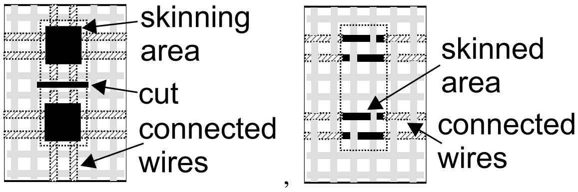


Figure 12: Placed cuts after iteration over pad A



(a) (b)

Figure 13: Connection method; (a) not optimized, (b) optimized

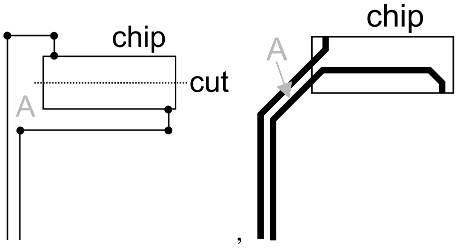
- Consider high resistance of thin copper wires
- Use script to insulate electrical nets

An additional optimization step, which reduces the number of cuts, shall be briefly explained. Consider a capacitor whose pads each cover four intersections of wires depicted in figure 13(a). Therefore, the pad size determines the skinning area on the fabric and two horizontal and two vertical wires are affected by the skinning for a pad. If the capacitor is connected in the manner described before in section 4., the four wires would be connected together and a cut between the pads would be necessary for electrical insulation. However, if we guarantee precise manufacturing processes and a routing layout, which connects the capacitor from the long side, only the insulation of the horizontal wires can be removed. Thus, no cut is needed anymore as seen in figure 13(b).

This optimization is feasible using a very precise textile fabric and at locations where the copper wire appears at the fabric surface (compare figure 1, where the copper wire is alternately on the top and underneath the surface). For the skinning step, laser precision should not be an issue since laser spot sizes are typically less than $40\mu m$.

6. EMC Aspects

This section discusses the some EMC (electromagnetic compatibility) aspects of woven fabric. It is worthwhile to clarify from the outset that fabrics possess worse electrical properties than a PWB. A low-ohmic power supply is fundamental for high-frequency electrical circuits. In order to achieve this goal, power planes are essential components in PWB designs providing low DC impedance and controlled characteristic impedances. However, the thin copper wires of $40\mu m$ in the fabric feature about $13\Omega/m$ according to AWG 46 (American Wire Gauge). For low DC impedance, several wires need to be connected in parallel eating up a lot of space. Besides, the maximum allowed current is less then 20mA per wire (AWG 46).



(a) (b)

Figure 14: Scatter field example on fabric (a) and PWB (b)

Since ground planes cannot be realized in fabrics, coplanar waveguide-like structures with controlled impedance can be established instead by using wires in parallel in a ground-signal-ground arrangement [3]. Although utilizing of several wires in parallel increases reliability against mechanical stresses, it introduces signal distortions when running at higher frequencies because of odd modes [3].

Note that wires, which are not connected to any nets, are floating and could act as antenna. However, this effect can be neglected at low frequencies. Similarly, reflections due to unconnected ends of traces can then be disregarded.

The perpendicular structure of the routing increases the effect of a scatter field. A rectangular guidance of the traces to a chip as depicted in figure 14(a) results in a bigger enclosed area between signal and ground. The 45^o angular structure on a PWB (figure 14(b)) decreases the enclosed area A as well as the total trace length l. In formula (10) and (11), the electrical dependencies are shown where ϕ is the magnetic flux, B the flux density, u_N the induced noise voltage and u_S the signal voltage. Therefore, the induced noise due to a scatter field is directly proportional to the enclosed area. In other words, an increased area between signal and ground lowers the signal-to-noise ratio (SNR). This fact must be considered when designing a circuit for textiles.

$$u_N = \frac{d\phi}{dt} = A\frac{dB}{dt} \qquad (10)$$

$$SNR = 20 \cdot log(\frac{u_S}{u_N}) \qquad (11)$$

7. Conclusion

In this paper we have shown a solution how to integrate simple routing structures into fabrics. Although the electrical behavior of fabrics is worse compared to PWBs, our targeted applications consisting of chips with few pins running at low frequency are feasible. A textile routing structure generally occupies more space and requires more vias whereas a PWB needs more layers. Efficient manufacturing of circuits on fabrics is still an open issue because of the flexible nature of fabrics and because of their worse form stability compared to PWBs. Pattern recognition of vias and cuts by online image processing could be an approach to overcome these problems.

In the future, we will further promote measurements and modeling of the fabric in order to determine the electrical properties of vias and pads. Another issue is washability of the electronics as well as reliability under mechanical stresses.

Systems-on-Textile have the potential to enable entirely new applications not only in medical environments, but also as a personal assistant in our daily life obtaining information about timetables of public transportation or giving guidance through a foreign city. Through unobtrusiveness and wearing comfort, wearable computing is able to become as established as today's mobile phones.

Acknowledgements

The authors would like to thank Mr. Daniel Odermatt from Sefar Inc. for his support and Mr. Ruedi Köppel for the fruitful discussions.

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