# Electronic Textiles for Wearable Computing Systems

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**Abstract**

*Based on the advances in computer technology, especially in the field of miniaturization, wireless technology and worldwide networking, the vision of wearable computers emerged. We already use a lot of portable electronic devices like cell phones, notebooks and organizers. The next step in mobile computing could be to create truly wearable computers that are integrated into our daily clothing and always serve us as a personal assistant. This paper explores this vision from the textile point of view. Which new functions could textiles have? Is a combination of electronics and textiles possible? What sort of intelligent clothing can be realized? Necessary steps of textile research and examples of current developments are presented as well as future challenges.*

## 1 New functions of clothing

Nowadays clothing is supposed to have more functions than just a certain climatic protection and a good look. One approach of systematisation is to distinguish between properties referring to the wearing process and properties referring to the product life respectively to the product durability. Table 1 shows the most important wearing and durability properties. The item thermal, mechanical and chemical effects on the body includes special innovative functions like anti bacterial, fragrant or even medical properties. Durability describes the change of properties due to cleaning and wearing processes.

A revolutionary new property of clothing would be the possibility to exchange information. If clothing would be capable of recording, analysing, storing, sending and displaying data, a new dimension of intelligent high-tech clothing could be reached. Clothing would extend the users' senses, augment

| product properties of clothing | |
|---|---|
| wearing properties | durability |
| interaction with environment and wearer | change of properties due to cleaning and wearing |
| e.g. optical effect (aesthetics, fashion, signal effect),<br>barrier effect,<br>ergonomics, fit,<br>thermal, mechanical, chemical effects | e.g. dimensional changes,<br>loss of strength |
| new: exchange of information (record, analyse, send, display data) | new: reliability of electrical functions |

Table 1: Product properties of clothing

the view of reality and provide useful information anytime and anywhere the user goes. Possible application fields are:

- working: displaying helpful data, connecting to the Internet or to other persons
- medicine: monitoring health parameters
- security: detecting danger, calling for help

Other fields as for example sports and entertainment offer an almost unlimited number of application ideas. But until now the so-called wearable computers that are on the market are rather portable devices than part of clothing. The new approach is to use textiles for electrical functions and to realize electronic clothing. Conductive textiles could transmit data and power and could serve as a substrate for electronic components. So the textile vision of wearable computing is to develop new textiles and new technologies for the manufacturing of intelligent clothing with electronic functions.

## 2 Combination of electronics and textiles

The combination of electronics and textiles seems not to be practicable in view of the opposite properties (table 2). Textiles are soft and flexible and are often assessed by subjective criterions like handle and optical appearance. An important feature of textiles is a high robustness, as they have to withstand wearing and washing processes. In contrast to that electronics consist of small rigid structures that are very sensitive and usually protected by hard boxes. Unlike the textiles electronics are characterized by well-defined exact properties that are achieved in precise fabrication processes.

| electronics | textiles |
|---|---|
| • rigid<br>• hard surface<br>• small structures<br>• sensitive<br>• protected by hard boxes<br>• precise fabrication<br>• well-defined properties | • flexible<br>• soft surface<br>• robust<br>• washable<br>• empirical product development<br>• undefined manufacturing processes<br>• subjective quality criterions |

Table 2: Properties of electronics and textiles

There are some efforts in today's research to overcome these difficulties but the main problems are not resolved yet. General investigations of the electrical properties of conductive textiles or even sophisticated technologies how to connect textiles and electronics are not reported yet. Most of the solutions consist of task specific demonstrators. The Philips jacket [1] is often cited as an example of electronic clothing that is already available on the market but in this garment the textile itself just serves as a carrier of cables and special connectors. In the following a systematic approach is presented how a real combination of electronics and textiles could be achieved.

# 3 Types of conductive textiles

Some textile products with electrical properties already have found application in the field of EMI shielding, static dissipation and resistive heaters. For these products the whole area of the fabric has to be conductive, whereas data transmission requires separate conductor lines. In table 3 a list of possible technologies of creating conductive textiles is compiled. For data transmission it is important to have a high conductivity. Continuous filaments that are completely made of conductive material (conductive polymers or metal) suit this purpose best. However these filaments are hard to handle in textile fabrication processes. Especially the conductive polymer fibres are very brittle and in addition to that expensive to manufacture. Fine metal filaments (with diameters from 10-60 $\mu$m) can be used for textile applications.

An important aspect is the possibility to apply insulating coatings on these filaments. The combination of such filaments with texturized synthetic filaments leads to processable yarns. Alternative methods of creating conductive threads are the filling of fibres with carbon or metal particles, the blending of short carbon or steel fibres and the coating of fibres with conductive polymers or metal. These fibres have better textile properties but worse conductivity.

| |
|---|
| Fibres:<br>• filaments/ short fibres made of metal or conductive polymers,<br>• metal- or carbon-filled fibres,<br>• fibres with metal or conductive polymer coating |
| Yarns:<br>• spun yarns,<br>• filament yarns (e.g. texturized),<br>• plied yarns |
| Fabrics:<br>• woven fabrics,<br>• knitted fabrics,<br>• braided tapes and cords,<br>• embroidered patterns |

Table 3: Conductive textiles

First efforts at using conductive textiles for electrical circuitry were made at MIT Media Lab in the E-broidery project [2]. Conductor lines were realized by embroidering metal fibres or weaving silk threads that are wrapped in thin copper foil. The main drawback is the need of a protection against shorting and corrosion, as the conductive fibres are not insulated. A new approach is to use metal filaments that are insulated with a coating layer. When woven into a fabric such material provides a tight mesh of individually addressable wires. These insulated fibres are able to withstand textile typical handling as for example washing and wrinkling without a damage of the insulation. We investigated the electrical properties of such conductive fabrics.

# 4 Electrical parameters of textile wires

In order to evaluate the performance and limits of this new technology of textile connection we have extracted the electrical parameters of textile wires. Time and frequency domain analysis were used to get these parameters and allowed us further to define for the first time a theoretical model that describes the transmission signal in textiles. In this study we investigated fabrics that have copper filaments in warp and weft direction (see figure 1).

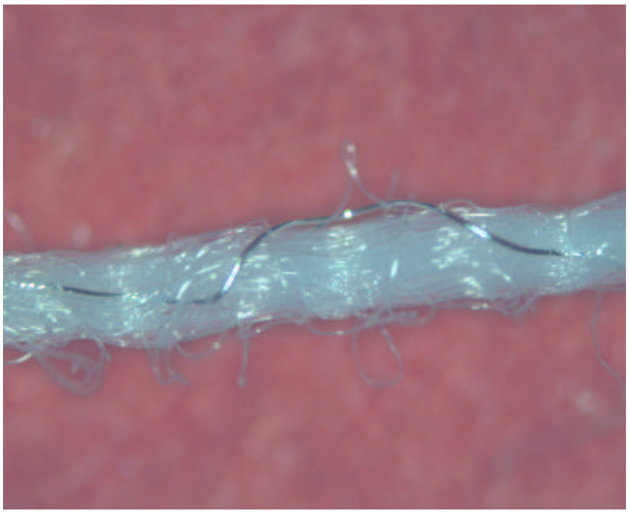

Figure 1: Polyester thread with metal filament

The length of the investigated textile was 20cm and the diameter of the copper wires is 40 $\mu$m. The DC resistance of one single wire was measured with a HP34420A micro ohm meter and is $R = 0.35$Ohm/cm. However for high frequency the interconnection is no longer a simple wire characterized by only its resistance. Distributed parasitic elements like capacitance and inductance have to be considered [3]. To extract these parameter values we chose TDR (Time domain Reflectometry) measurement methods. This method has the advantage to define transmission lines in terms of characteristic impedance $Z_0$, time delay and reflection coefficient.

In our first study we performed TDR measurements on a single transmission line surrounded on each side by one textile wire acting as return path (ground). Figure 2 shows the measurement setup. We measured $Z_0$ (characteristic impedance) and $td$ (propagation delay) for 50Ohms load and a pulse signal of 250mV amplitude and a rise time of 0.35ns. Impedance information was extracted by calculating the reflection coefficient as function

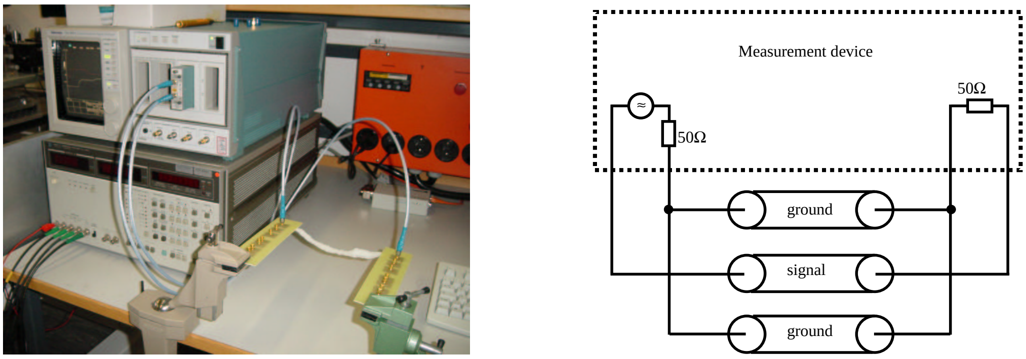

Figure 2: Measurement setup

of the incident and reflected voltages. The time delay between transmitted and reflected energy is a function of distance and propagation velocity. For the configuration with one single textile wire the measured characteristic impedance $Z_0$ is 200Ohm, the time delay 1.7ns and the rise time 80ps. The values $td$ and $Z_0$ allowed us to calculate the total shunt capacitance and total series inductance of the transmission line [4]:

$$C_{total} = \frac{td}{Z_0} \tag{1}$$

$$L_{total} = td \cdot Z_0 \tag{2}$$

The capacitance value is 8.5pF, the total inductance value 340nH and the resistance $R = 0.35\text{Ohm}/\text{cm}$. These measured values correspond well with typical values of conventional wires. For example the inductance of bond wires is about 1nH/mm. The inductance of the textile wire is something higher due to the loop shape of the metal filament. These first results and the motivation to design connections with new textile transmission lines technology leads us to define the performance and limits of a basic textile wire. Therefore we also consider and characterize transmission lines composed of 3 and 6 wires connected in parallel. The three investigated configurations can be found in table 4 and figure 3.

| Configuration number | Number of signal lines | Number of ground lines |
|---|---|---|
| 1 | 1 | 2 (1 on each side) |
| 2 | 3 | 2 (1 on each side) |
| 3 | 6 | 2 (1 on each side) |

Table 4: Configuration of signal and ground lines

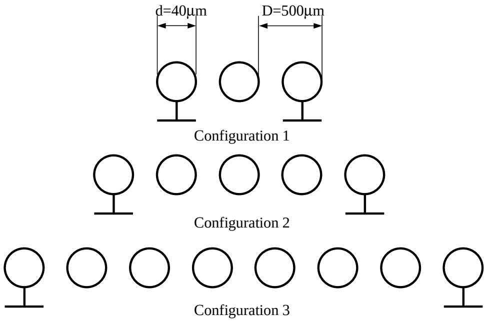

Figure 3: Signal and ground line configurations

Figure 4 depicts the impedance and capacitance profile in function of the number of lines. The $Z_0$ decrease is accompanied by an increase of the total transmission line capacitance. The increase of the capacitance is caused by the increase of the signal line surface. Above a certain number of lines there is no more significant rise of the capacitance because signal lines that are too far away from the ground lines do not influence the total capacitance any more. We note also that the time delay remains constant (1.7ns) for all the configurations but the rise time ($tr$) increases (figure 5a).

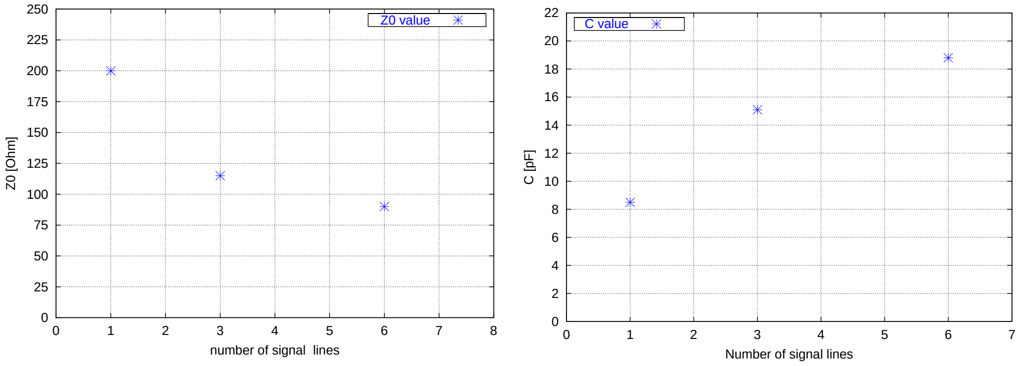

Figure 4: a: Characteristic impedance, b: Total capacitance

Network analyser measurements around 800MHz revealed 0.075dB/cm and 0.16dB/cm losses for configuration 2 and 3 respectively. In order to validate the transmission signal integrity we checked the shape and the amplitude of the signal output of a 100MHz clock signal. The rise time is 1ns with 250mV amplitude in the precedent described configurations. From figure 5b we can see that the signal output amplitude is nearly the same for 3 and 6 lines, the signal output for 1 wire is lower. The general shape of the signal is quiet well preserved and presents characteristic shape of transmission lines output.

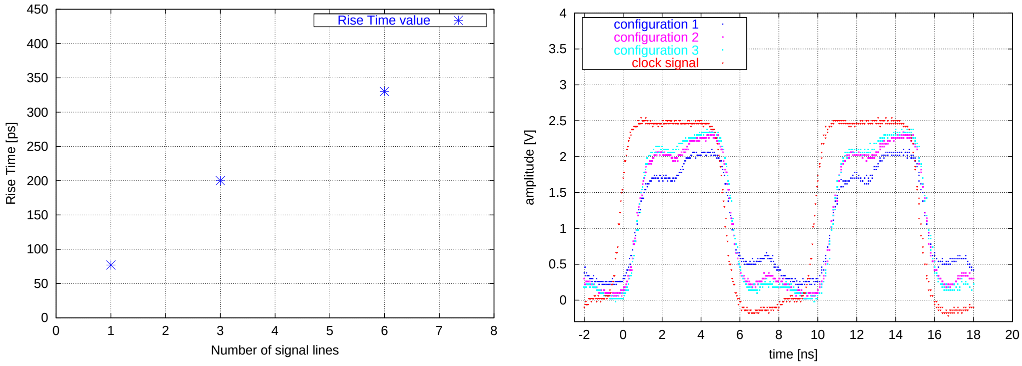

Figure 5: a: Rise time, b: Output signal

Based on these waveforms and on the extracted value parameters $L, C, R$ we built a theoretical model for this new textile interconnect technology. Transmission lines can be modelled with distributed capacitance and inductance per unit length as an equivalent circuit. The measured characteristic impedance and propagation delay define the total shunt capacitance value and the total series inductance values. We simulated the circuit model with SPICE and were able to fit the model to the measured signal output. With the developed model it is possible to determine the electrical performance of different line configurations.

# 5 Results

The definition of a theoretical model of signal transmission in textiles allows performance predictions and the optimisation of the signal line configuration. The experiments have shown good signal integrity of textile transmission at 100MHz along a distance of 20cm. For this constellation three parallel signal lines provide the best results. With more wires the rise time increases, with less wires the losses are higher. For other parameters and geometries the model outputs the respective performance information and optimal configuration. With the results it is possible to manufacture fabrics with defined electrical properties and to optimize the geometrical arrangement of the conductor lines. In further experiments the influence of the surrounding textile material (e.g. density, polymer type) will be investigated. Preliminary tests showed that there is a difference between fabrics that have metal filaments in warp and weft direction or just in one direction. In the future also alternative conductive fibres (e.g. fibres with a conductive coating) and alternative textile constructions (e.g. knitted fabrics) will be considered.

## 6 Conclusions and future challenges

The new approach to use insulated metal filaments woven into textiles opens the door to new technological perspectives of data transmission through clothing. In the first step the electrical properties of such conductive fabrics have been investigated. The development of a theoretical model of textile transmission lines allows to predict the performance of textile wires and to optimize the signal line configurations. With these results it is possible to connect sensors and computing units with textile wires. The next step will be the development of electrical circuits in textiles and the attachment of electronic components. The integration of the electronic components into clothing and the use of textile transmission lines offer great advantages. For truly wearable and context aware computers a combination of electronics and textiles is necessary. Therefore an interdisciplinary research work between electrical and textile engineers, as it is carried out at the Wearable Computing Lab in Zurich, is inevitable.

## References

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