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Wearable computing systems – electronic textiles

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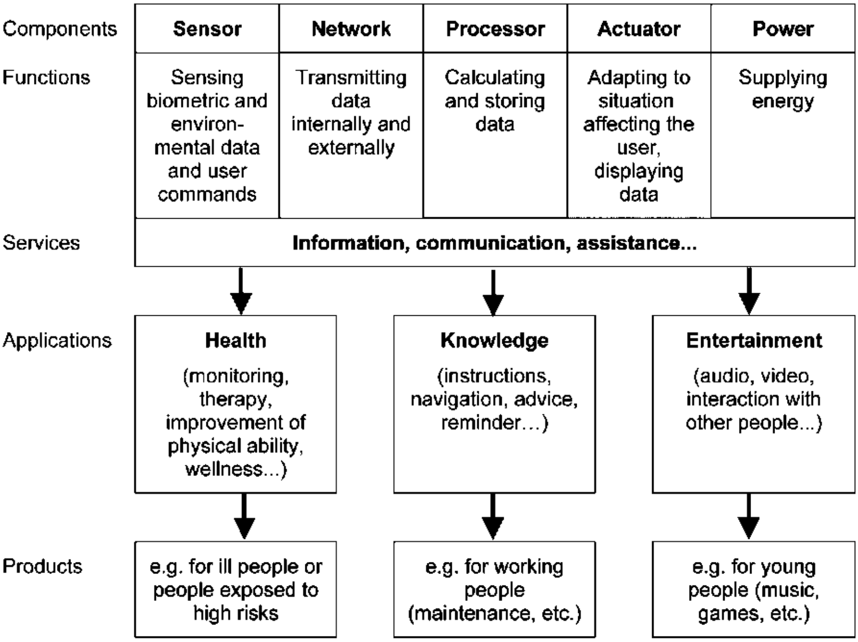
9.1 Introduction

The vision behind the idea of wearable computing systems describes future electronic systems as an integral part of our everyday clothing, serving us as intelligent personal assistants. A wearable computer is always on, does not hinder the user's activities, has easy-to-use interfaces, is aware of the user's situation and provides support, e.g. by displaying relevant information, monitoring health parameters and augmenting the user's view of reality. The first wearable computers were developed for navigation and maintenance tasks (e.g. aircraft inspection[1]) and for military applications. The Defense Advanced Research Projects Agency (DARPA) supports wearable computing research in the United States in order to achieve a breakthrough in developments in body-worn computational resources for soldiers. In the meantime, wearable computing is predicted to have a future in daily life acting as a general-purpose system rather than a single-purpose system. Mann[2] regards wearable computers as a 'second brain' and their sensory modalities as additional senses augmenting human intellect. In this way, wearable computers can contribute to the vision of an 'ambient intelligence', where intelligent devices are integrated into the everyday environment and provide a multitude of services for everyone. Starner[3] describes the possibilities offered by wearable systems and discusses challenges in wearable research.

Figure 9.1 shows the possible systemisation of wearable computers. The first level consists of the components of a wearable system that provide several functions:

- sensor unit: registration of biometric and environmental data and of user commands
- network unit: transmission of data within the wearable computer and to external networks
- processing unit: calculating, analysing and storing data



9.1 Systemisation of wearable electronic systems.

- power unit: supplying energy
- actuator unit: adapting to situations, creating an effect on the user, displaying data.

On the system level, several of these functions are combined to form services. Providing information, communication or assistance are possible services. Because mobility is now a fundamental aspect of many services and devices, there are an almost unlimited number of application ideas, e.g. in the fields of health, knowledge and entertainment. Health applications include the monitoring of ill or high-risk persons, people exposed to extreme conditions or people engaged in sports, but also therapy and improvement of physical abilities. Examples of knowledge applications are navigation or instructions for work. There are a large number of applications also in the area of entertainment (e.g. audio and video). The last level shows possible target groups for wearable electronic products.

9.2 Why is clothing an ideal place for intelligent systems?

Clothing is an important and special part of our environment, as it is personal, comfortable, close to the body and used almost anywhere and anytime. Nowadays, clothing has more functions than just climatic protection and good looks. Zhang and Tao[4–7] give an overview of clothing that is considered to be smart. For example, shape memory textiles and phase change materials adapt their properties depending on the temperature and have found application in climate-regulating garments. But clothing is still far from taking full advantage of the potential of information technology services. If clothing had intelligent features, it could serve us in a very unobtrusive and natural way. Clothing could 'enhance our capabilities without requiring any conscious thought or effort'.[8] Being close to the body, clothing enables the intimate interaction of man and machine. This interaction is necessary for any kind of computer intelligence to be used for context recognition or as intuitive interfaces. The WearNET is an example of a sensor system attached to the body that can provide a wearable computer with a wide range of context information.[9]

However, most of the wearable computers on the market are not integrated into clothing. They still consist of bulky and rigid boxes and are portable machines rather than a comfortable part of the clothing (e.g. Xybernaut[10]). Gemperle *et al.*[11] describe how the shape and placement of such devices can be improved in terms of wearability. The WearArm that has been developed by ETH and Massachussetts Institute of Technology (MIT) is a wearable computer that combines complex functionality and high speed with advanced wearability.[12] This computer consists of miniaturised modules connected using flexible substrates and equipped with advanced, context-sensitive power-management features.

The next step towards real wearability is the integration into clothing. There are two methods of integration:

- the miniaturisation of electronic components and their attachment to textiles
- the development of textiles with electronic functions (electronic textiles).

Clothing for the arctic environment,[13] the Philips jacket[14] and the 'Lifeshirt'[15] are some examples of the first method. In these products the textiles simply serve as a carrier of conventional cables, special connectors and miniaturised electronic devices. Humans prefer to wear textiles, as they are flexible, soft, lightweight, breathable, robust and washable. Thus, the idea emerged of developing fibres and fabrics that can be used for electronic functions. A suitable definition considers electronic textiles as materials possessing both electronic functionality and textile characteristics.

9.3 Electronic textiles

In order to describe electronic textiles it is necessary to define the term 'textile'. Materials are considered to be a textile when they consist of drapeable structures that can be processed on textile machinery. Textiles are usually made of fine and flexible fibres and threads that have a high length/diameter ratio but textiles can also contain membranes and foils. Ready-made textile products include ropes, ribbons, fabrics and also three-dimensional products such as clothing.

'Electronic' means that a system is able to exchange and process information. If textiles had the ability to record, analyse, store, send and display data, a new dimension of intelligent high-tech clothing could be reached. However, there are some general difficulties in creating electronic textiles for clothing. Electrical functions have to be embedded in textiles in such a way that the flexibility and comfort of the fabrics are retained. Fibres and fabrics have to meet special requirements concerning not only conductivity but also processability and wearability:

- The fibres have to be able to withstand handling that is typical for textiles, for example weaving, washing and wrinkling, without damaging functionality.
- Fibres that are used for clothing have to be fine and somewhat elastic in order to be comfortable to wear.
- Fabrics need to have a low mechanical resistance to bending and shearing so that they can be easily deformed and draped. The closer the textiles are to the body, the more flexible and lightweight they have to be.

These demands are partly inconsistent with the materials and geometries that are needed for conducting data and power. There are two possible kinds of conductivity: electrical or optical conductivity. Optical fibres have some advantages, as there can be no shorts, no corrosion and no parasitic field effects. But electrical conductors are easier to handle in textile fabrication processes. In addition, the costs are higher for optical fibres owing to expensive light sources and transceivers. Most plastic optical fibres are stiff, allow a limited bending radius and are difficult to weave or knit. Metal, carbon and conductive polymers are also quite rigid and brittle materials. They are heavier than most textile fibres, making homogeneous blends difficult to produce. Nevertheless, textile technologies have been developed to manufacture processable fibres and yarns from these materials.[16,17] Conductive fabrics already have found applications, especially in the field of electromagnetic interference (EMI) shielding and static dissipation. Methods of creating electrically conductive fibres are:

- filling synthetic fibres with carbon or metal particles
- coating fibres with conductive polymers or metal
- using continuous or short fibres that are completely made of conductive material.

These fibres can be woven, knitted or embroidered into fabrics. Conductive ink technology offers another alternative in the development of electronic textiles. The benefits offered by digital printing techniques have prompted many conductive ink developers to experiment with printing onto textile substrates (e.g. Colortronics[18]).

9.3.1 Textile networks

Electrical networks are responsible for data and power transfer. On-body communications in wearable systems can be wired or wireless. A textile network means that fabrics are used to replace conventional wires, whole circuit boards or antennas. The first efforts to use conductive textiles for electrical circuitry were made at the MIT Media Lab in the E-broidery project.[19] Conductor lines were realised by embroidering metal fibres or weaving silk threads that were wrapped in thin copper foil. Gorlick's 'electric suspenders'[20] contain stainless steel conductors for power and data buses. The main drawback of these prototypes is the need for protection against shorting and corrosion, as the conductive fibres are not insulated. Jayaraman and co-workers[21] developed a garment that included electrically conductive fibres and plastic optic fibres to transfer information from sensors to processing units. In this so-called 'wearable motherboard', each electrical fibre (e.g. stainless steel, copper or doped nylon fibre) is insulated with a polyvinylchloride (PVC) or polyethylene coating. At ETH Zurich extensive studies were carried out to measure and model the high frequency properties of conductive fabrics (see Section 9.4). With the developed model it is possible to simulate and optimise communication networks in textiles.

In the area of communication architecture there are approaches to investigate networks of distributed computing elements embedded into fabrics. Marculescu *et al.*[22] describe computational models of large-area information systems that adapt to changing conditions and reconfigure on-the-fly to achieve better functionality. The reconfigurable fabric of UCLA[23] contains organic electronic devices connected to flexible polymeric substrates. These devices have reconfigurable software so that the network can configure itself based on initially available resources and ongoing damage monitoring.

Kallmayer and Griese[24] realised transponder antennas by weaving conductive fibres into multilayer fabrics. Hum[25] used several short-range fabric antenna coils to create a wireless communication infrastructure between various positions on clothing and between different pieces of clothing (FAN = fabric area network, multiple radio frequency identification technology (RFID) links). These antennas can be used to communicate with transponder chips that are embedded, for example in personal items. Massey[26] integrated mobile phone antennas in clothing by using the relatively large surface area of the fabric to include a ground plane and an antenna element made of copper-plated textiles.

9.3.2 Textile sensors and actuators

The next substantial progress will be to use textiles not only for transmitting signals but also for transforming them. Transformation of signals can happen in two ways:

- sensor = transformation of physical phenomena into processable electrical signals
- actuator = transformation of electrical signals into physical phenomena.

Textile technologies have been developed to create fibres and fabrics with a significant and reproducible change of properties caused by defined environmental influences. Sensors can be used to measure biometric or environmental data, but also to act as an input interface. Actuators can adapt themselves to a situation, affect the human body or serve as a display.

'SOFTswitch'[27] is one example of a textile pressure sensor. It is made of conductive fabrics with a thin layer of elastoresistive composite that reduces its resistance when it is compressed. The 'sensory fabric'[28] also consists of two conductive fabric layers separated by a nonconductive layer. This product has an even simpler construction because the nonconductive layer is formed by a mesh so that pressure can create a contact in the holes of the mesh. This pressure-sensitive fabric can be used for such items as soft keypads. The 'sensor jacket'[29] measures stretch from resistive changes in knitted strips. Gorix[30] is a woven textile formed from pre-oxidised carbonised polymers that can be used, not only for resistive heating, but also as a temperature or pressure sensor.

In the 'Wearable Motherboard',[21] plastic optical fibres detect damage (broken paths) in the fabric and can give information about the location of bullet penetration. Tao *et al.*[31] describe the use of fibre optic sensors inside fabric-reinforced structures that monitor mechanical, acoustic, electric, magnetic and thermal perturbations. Fibre Bragg-grating sensors are manufactured by modifying the core in a single-mode optic fibre to detect the wavelength shift induced by strain or temperature change. Sensing can be distributed along the length of the fibre and it is possible to measure different parameters simultaneously. The possibilities of integrating fibre optic sensors in clothing seem promising. El-Sherif *et al.*[32] have embedded fibre optic sensors into soldiers' uniforms. These sensors can detect chemical, biological and thermal hazards. The optical fibres have a sensitive cladding that can change the light propagation characteristic of the fibre.

During the last few years polymers have emerged that respond to electrical stimulation with property changes (e.g. shape, size, colour change). These polymers are called 'electroactive polymers' and can be used as sensors or actuators.[33] Gregory *et al.*[34] developed fibres that can quickly change their colour or optical transparency by the application of an electrical or magnetic field. De Rossi *et al.*[35] describe fabrics coated with a thin layer of conducting polymer that possess strain and temperature sensing properties and also actuating properties. These fabrics contain fibre bundles that contract and relax under electrical control and can be used as a tactile output interface (e.g. in a sensor glove).

France Telecom[36] has developed a display made of optical fibres woven into a fabric. However, owing to the mechanical limitations of the optical fibres, the number of pixels is just 64 and the fibre diameter is 0.5 mm. Another technology that could possibly be adapted to textiles is the fabrication of organic light-emitting diodes (LEDs). Processes have already been developed to create such displays on flexible substrates but not yet on textiles. Textile displays also can be realised using conductive fibres covered with a fine layer of an electroluminescent material.

9.3.3 Textile processors

Processing includes arithmetic operations and the storage of data. Transistors, diodes and other non-linear devices are needed for these functions. Manufacturing technologies have already been developed to create organic devices ('all-polymer' transistors and batteries). Such devices, as well as thin silicon integrated circuits (ICs) can be fabricated on flexible polymer substrates.[24] Such flexible chips can be attached to textiles but they are not textiles themselves. Preliminary efforts are being made to create textile fibres from electroactive polymers that can act as transistors. One of the main challenges is to improve the stability of such conductive fibres. Apart from the short lifetime, the slow switching speed is another limitation of performance. A company[37] has created threads with transistor functionality and has been able to make them more stable so that they can perform millions of switching operations.

9.3.4 Textile power supply

As the power supply is usually the biggest and heaviest part in the wearable computers of today, there are several approaches to decreasing power consumption by power management or power performance trade-offs and to developing novel power supply technologies (e.g. lithium polymer batteries, micro fuel cells[38]). The alternative to batteries is to use different sources of energy available on the body which can be transformed into electrical energy, e.g. sunlight, body temperature, body motion.[39] Some efforts have been made to embed miniaturised or flexible energy supplies into textiles, but few to create a textile power supply. Infineon[40] presented miniaturised silicon thermoelectric generators attached to clothing. Using the difference in temperature between the outside and the inside of clothing, these thermogenerators produce an output power of a few microwatts per square centimetre. Thin film solar cells can be made on flexible surfaces such as plastics. Baps *et al.*[41] adapted the technology for the flexible solar cell to fibre form. The efficiency of these alternative energy sources needs to be improved. Creating components that are wirelessly powered by an electric field in the environment is another interesting approach. For example, sensors or devices could 'wake up' only when the user is close to an electrical field.

9.3.5 Potential of electronic textiles

This overview shows that electronics cannot only be attached to textiles but also realised in the form of textile structures. Of course, the performance and costs of such textile structures cannot be compared with those of conventional computer technology. There are strong limitations concerning mass production and reliability. But apart from the difficulties though, there is also potential for the use of electronic textiles. Textiles offer new and fascinating possibilities in creating information systems. The geometric and mechanical properties of textiles (large flexible area) differ strongly from conventional electronics and can create new computer designs and architectures.[22,23]

In the future, it could become quite difficult to separate clearly electronic textiles from the aforementioned method of miniaturisation and attachment, because computers could be miniaturised until they are the size of molecules. In this case, ‘attachment’ to fibres or fabrics would also result in electronic textiles.

9.4 Electrical characterisation of textile networks

This section presents the results of an interdisciplinary research work of textile and electrical engineers at ETH Zurich. We wanted to characterise communication networks in fabrics. We developed methods for measuring and modelling the high frequency properties of textile transmission lines in order to discover the limits and potential of textile-based communications. Our aim is to replace conventional wires and even high-performance circuit boards with textile fabrics. Therefore, we applied methods of microwave technology. That means that wires are not only characterised by their ohmic resistance but by wave effects depending on the line geometries and the surrounding material. Therefore, we also had to consider the geometric structures that are created in the textile fabrication processes.

9.4.1 Textile geometry

The geometry of textile materials is characterised by a hierarchical structure: bundles of fibres are twisted to create yarns; yarns are woven or knitted to create fabrics. Fabrics for signal transmission in wearable computers have to meet requirements concerning processability and wearability (see Section 9.3). It is necessary to have individually addressable conductors that are insulated to prevent shorts.

For our experiments, we fabricated yarns that contain insulated metal filaments and fulfil the aforementioned requirements. The characterisation methods that we developed can be applied to all kinds of conductive textiles. We chose woven fabrics with a plain weave in our experiments because this construction represents the most elementary and simple textile structure. In addition, this kind of material can provide a tight mesh of individually addressable wires that can be used for basic transmission lines as well as for whole circuits.

The fabrics that were examined contain polyester (PES) yarns that are twisted with a conductive fibre (copper). The conductive fibres have a diameter of 40 μm and are insulated with a polyesterimide coating. PES yarns with two different thicknesses (167×10^{-4} g m^{-1} resp. 334×10^{-4} g m^{-1}) have been used to create six different fabric types (Table 9.1). All fabrics have about 20 threads per cm in both directions but their densities differ according to the PES fineness used. Two of the fabrics have conductive fibres in both directions (warp and weft), two have

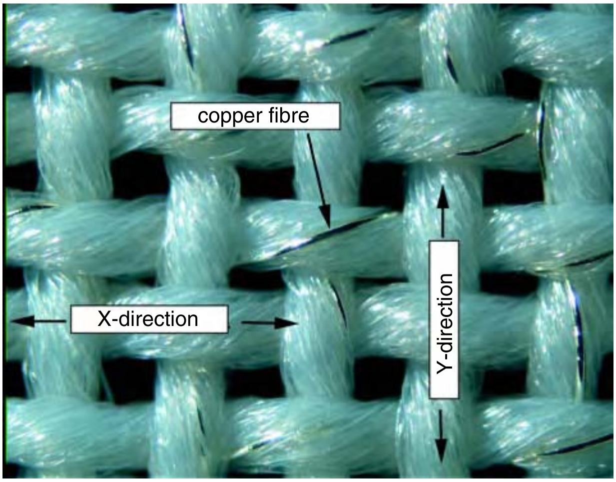
Table 9.1 Textiles used in the experiments

Woven fabrics:	Yarn types	Description
Fabric 1	Yarn A and B	Low density with Cu in both directions (*XY*)
Fabric 2	Yarn A and B	Low density with Cu in one direction (*X*)
Fabric 3	Yarn A and B	Low density without Cu
Fabric 4	Yarn C and D	High density with Cu in both directions (*XY*)
Fabric 5	Yarn C and D	High density with Cu in one direction (*X*)
Fabric 6	Yarn C and D	High density without Cu

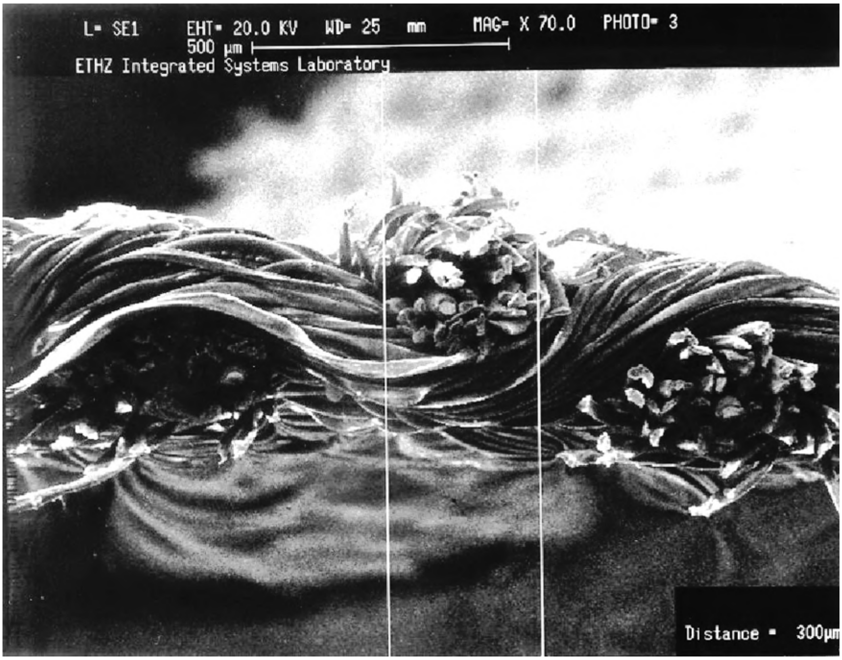
Note: Yarn A: PES yarn 167 × 10^{-4} g m^{-1} + Cu filament; Yarn B: PES yarn 167 × 10^{-4} g m^{-1}; Yarn C: PES yarn 334 × 10^{-4} g m^{-1} + Cu filament; Yarn D: PES yarn 334 × 10^{-4} g m^{-1}.

conductive fibres in just one direction (warp) and two are without conductors. Figure 9.2 shows fabric 4.

Taking a closer look at textile geometry one can observe that fibres follow a helical path within the yarn. The helical path of the metal fibres can be seen in Fig. 9.2. When the yarns are woven into a fabric they are periodically crimped (Fig. 9.3). This means that the length of the conductive fibres is greater than the length of the fabric. There are several irregularities concerning the location of the fibres within the yarn as well as concerning the location of the yarns within the fabric. These variations are caused by the deformability of the textile material and the degrees of freedom in the manufacturing processes. At the level of fibres and yarns there are variations in diameters and densities (along the thread but also from thread to thread). At the level of fabrics, the distance between yarns varies (Table 9.2). As textile materials have a viscoelastic behaviour, inner tensions relieve over time and the geometry may change (especially as a result of washing).



9.2 Woven fabric with conductive fibres.



9.3 Fabric cross-section.

Table 9.2 Examples of geometric variations in the textiles used in the experiments

Fabric type	Dimensions (µm)	Variations (µm)
Fabric 1 (low density)	$a = 891$ $d = 228$	$\sigma = 32.9$ $\sigma = 25.3$
Fabric 4 (high density)	$a = 876$ $d = 334$	$\sigma = 25.0$ $\sigma = 28.0$

Note: d = yarn diameter, a = yarn distance.

9.4.2 Electrical characterisation

In order to evaluate the performance and limits of textile transmission lines we extracted the electrical parameters with time and frequency domain analysis and developed a theoretical model that describes signal transmission in textiles.

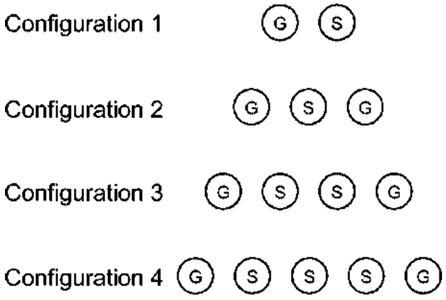
Material properties

The direct current (DC) resistance of a single metal fibre was $0.15\ \Omega\ \text{cm}^{-1}$ for yarn A and $0.17\ \Omega\ \text{cm}^{-1}$ for yarn C. These measured DC resistances and the actual diameter of the metal fibres allowed the effective conductor length to be calculated in comparison with the textile length. For the thinner yarns (type A) the conductor was about 7.5% longer than the corresponding textile, with a tolerance of 0.5%. For the thicker yarn (type C) where the conductive fibre ran a larger helical path, this difference increased to about 25.5% with a tolerance of 2.0%.

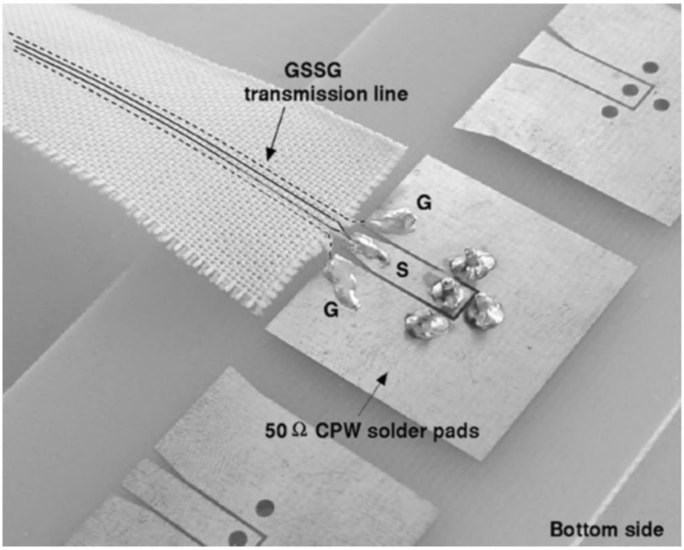
The dielectric permittivity ε_r of the mixed PES–air textile structure was extracted by means of parallel plate capacitors of known dimensions and using the yarn types B and D (without conductive fibres). The results obtained range from $\varepsilon_r = 1.4$ to 1.6. This inaccuracy was due to the fact that the measured permittivity strongly depends on the ratio of polyester and air. Introducing conductive fibres would also have affected the total permittivity, as the polyesterimide used for the isolation coating showed an $\varepsilon_r > 3$.

Transmission line configuration

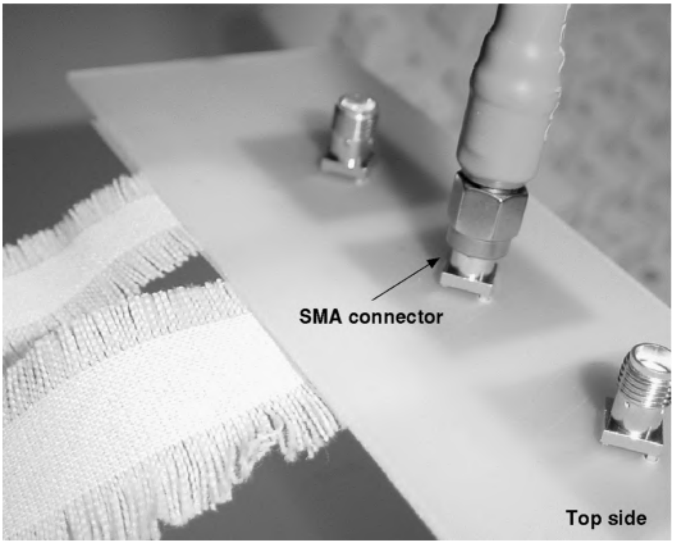
To minimise parasitic coupling at high frequencies the ground line should be close to the signal line. In conventional circuit boards a whole ground layer is often used, but creating such a construction in textile fabrics would have several disadvantages. We decided to take conductive fibres in the warp direction (*X*-direction) as signal lines and the neighbouring conductive fibres on each side as ground lines. These configurations are similar to the conventional coplanar waveguides (CPW) on printed wire boards. The transmission line configurations differ by the number of signal fibres S or ground fibres G. The space between the ground and the signal line is given by the textile construction and cannot be modified. Any attempt to skip conductive fibres to increase the space would yield floating lines evoking undesired parasitic coupling effects. A list of all investigated configurations is given in Fig. 9.4.



9.4 Transmission line configurations.



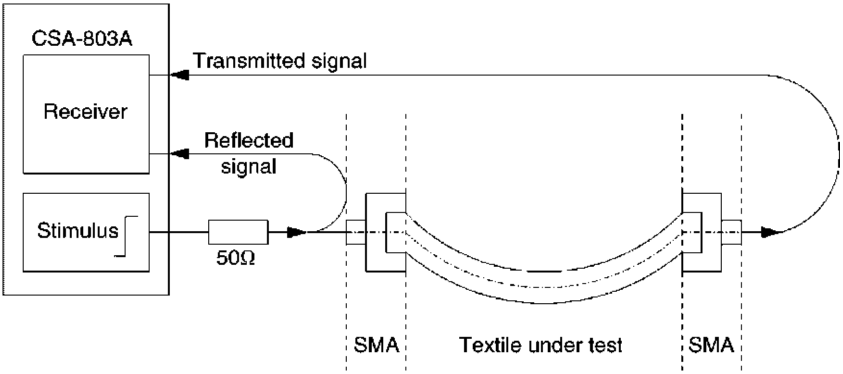
9.5 Textile solder pads as a 50 Ω coplanar waveguide.



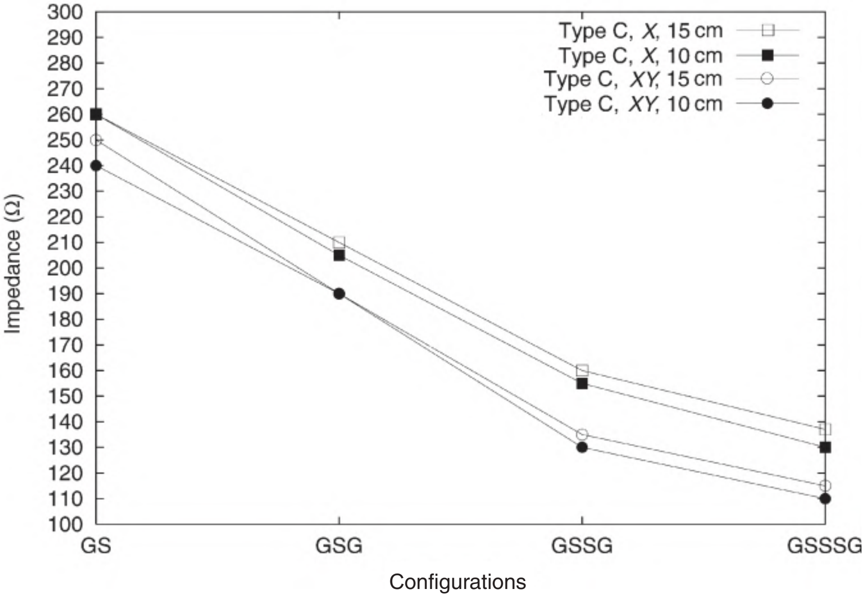
9.6 SMA connectors.

Impedance measurement

We investigated the characteristic impedance of the textile transmission lines. As we expected the textile geometric variations to influence on the impedance, we



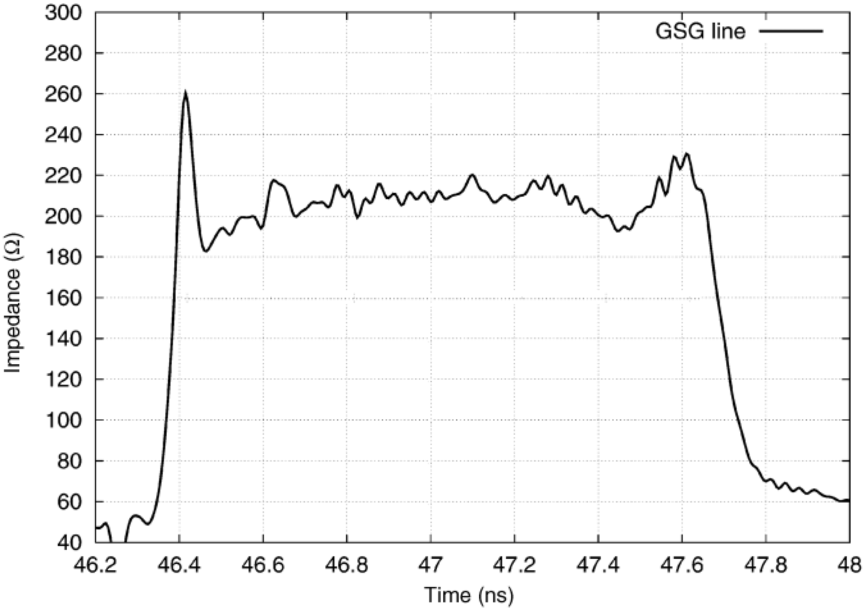
9.7 Time domain reflectrometry (TDR) measurement setup.



9.8 Measured impedance of different transmission line configurations.

measured the signal reflections along the transmission line with time domain reflectometry. We had to develop suitable connectors to measure the textile lines. FR4 laminate-based interposers with patterned 50 Ω CPW solder pads on one side and surface mount assembly (SMA) connectors on the other side allowed the textile samples to be reliably connected to the measurement equipment (Fig. 9.5 and Fig. 9.6). The block diagram of the measurement setup is depicted in Fig. 9.7.

Figure 9.8 shows typical measured line impedances for the investigated transmission lines. Results for the same yarn and fabric types are connected by lines to



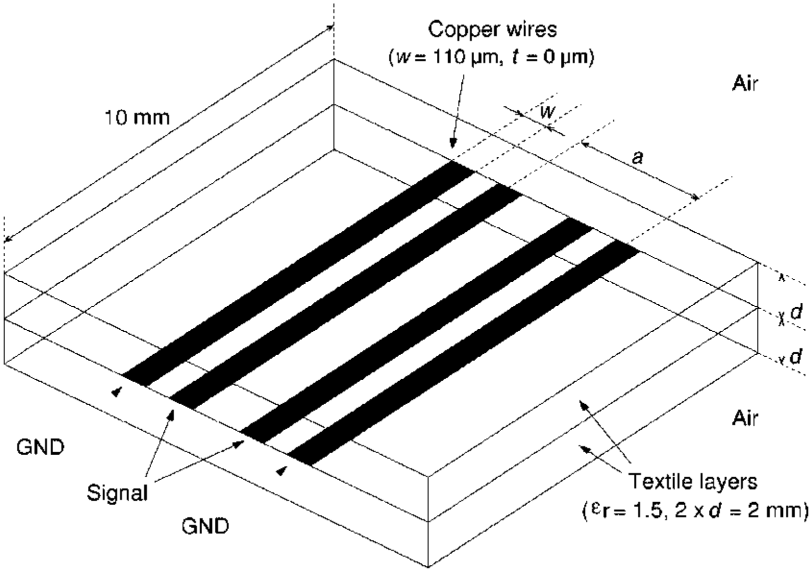
9.9 Impedance profile of 15 cm transmission line.

illustrate the relationship between configuration and line impedance. The *XY* fabrics (metal fibres in both directions) have lower impedances owing to a higher capacitance caused by coupling effects to the floating lines in the *Y* direction. The textiles with conductors only in the *X* direction have a lower capacitance and inductance and therefore provide faster signal propagation than the textiles with metal in the *XY* direction.

The results of the four configurations are comparable to coplanar waveguides on printed circuit boards (PCBs): increasing the signal line width by adding more parallel conductive fibres decreases the line impedance. Using fabrics with smaller distances between the threads (that means between signal and ground lines) would enable a lower line impedance, but 50 Ω lines seem difficult to achieve. The measurements show impedance variations along the textile signal lines (see Fig. 9.9). These variations are caused by geometric irregularities in the fabrics. We investigated the effects of these variations on the predictability of the line impedance.

Impedance simulation

In order to predict the impedance of different fabrics and line configurations we modelled the textile transmission lines with a 2.5 dimensional electromagnetic field solver (Sonnet EM Suite 7.0). We wanted to get a better understanding of how textile fabrication tolerances affect the line impedance. To simplify the modelling



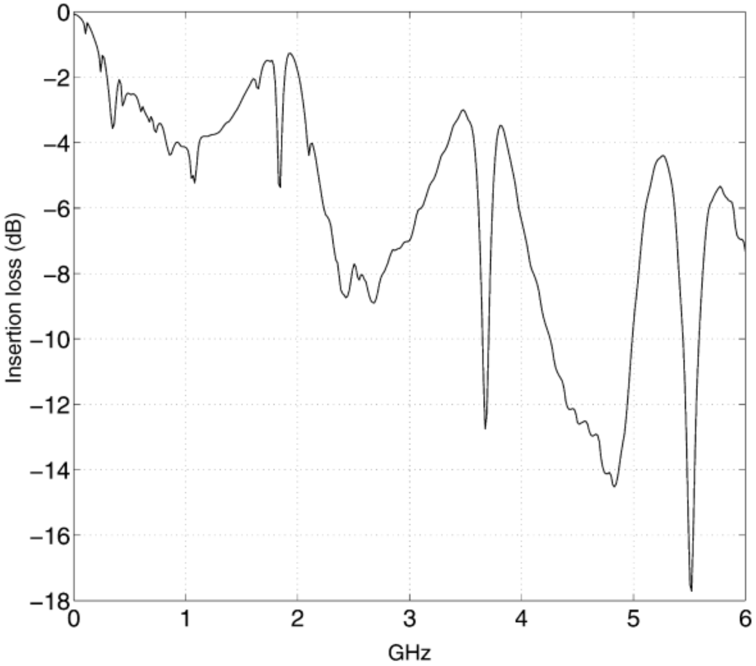
9.10 Textile model for Sonnet showing a GSSG configuration. *a* = distance between copper wires.

and to reduce the computation time, the structure of the woven fabric was regarded as a homogeneous material with an equivalent dielectric permittivity as previously measured on page 187. In effect the textile model consists of two dielectric layers with a permittivity $\varepsilon_r = 1.5$ and a thickness of 2 mm (see Fig. 9.10). The conductive fibres are modelled as planar strips between the two textile layers. To compensate for the helical shape of the conductor within the yarn, the width of the conductive stripes is averaged to $w = d/\pi \approx 110$ μm, where d is the yarn diameter.

Table 9.3 shows simulated impedances for fabric type C and demonstrates the impedance variations caused by the textile process tolerances. Z_{min} and Z_{max} have been calculated with the 'worst case' textile geometry. With the developed model it is possible to predetermine the textile line impedances and the achievable tolerances.

Table 9.3 Simulation results of textile line impedances with regard to textile process tolerances

Yarn type	Configuration	Z_{nom} [Ω]	Z_{min} [Ω]	Z_{max} [Ω]
C	GS	263	247	278
C	GSG	190	173	200
C	GSSG	163	157	172



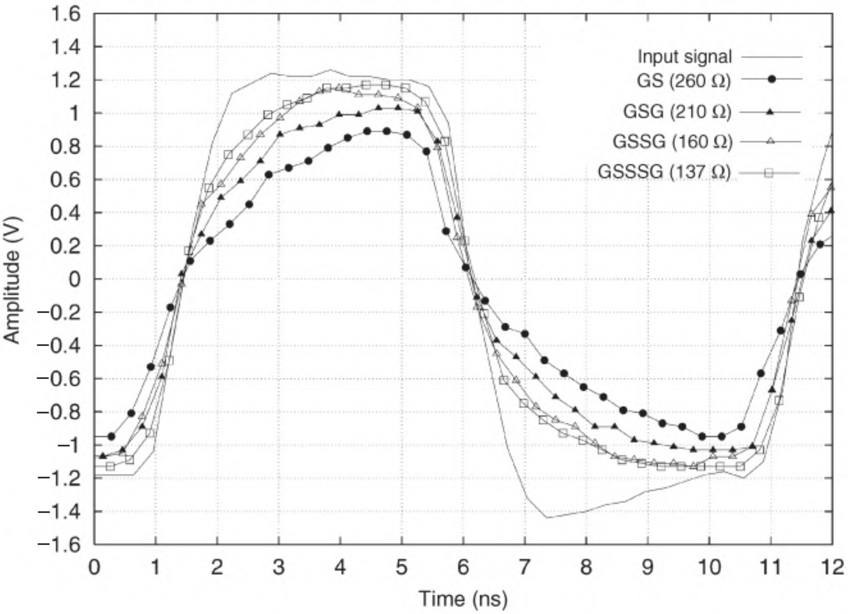
9.11 Measured insertion loss of the 5 cm GSSSG line (fabric 5).

Frequency characterisation

To investigate the frequency characteristics of textile transmission lines we measured the transmission properties with a vector network analyser (VNA) up to 6 GHz. The textiles were connected with the network analyser ports by means of the same FR4 interposers proposed earlier.

As mentioned before, the textile lines are not reflectionless, but stochastically change their impedance value. The variations of wire lengths and distances are able to make the phases unequal and excite parasitic waves ('odd modes'). As the ground wires and signal wires are shorted at the beginning and end of the transmission line, these odd modes have an effect when the line length is a multiple of the half wavelength of the signal. In Fig. 9.11 one can clearly observe some deep minima in the line transmission even down to –18 dB as a result of these parasitic resonances.

We extracted the attenuation constants for the different configurations. The extracted values show that in the lower frequency range, the coupling to the odd modes is weak and single mode propagation can be reasonably justified. One can observe that the extracted attenuation, even in this frequency range, shows non-monotonical frequency behaviour, which is not typical for uniform transmission

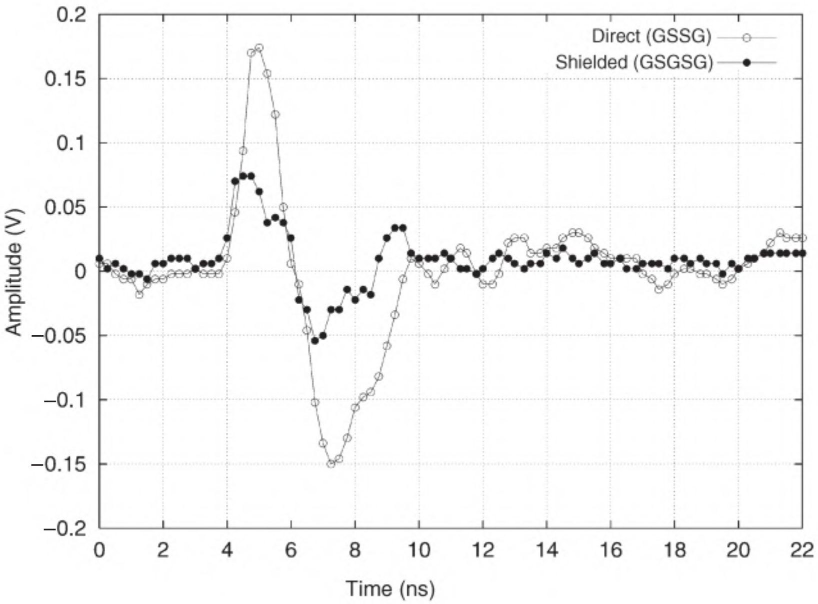


9.12 100 MHz clock signals measured through four different 20 cm-long textile transmission lines.

lines. This is the effect of non-uniform characteristic impedance profiles along the lines caused by large geometric tolerances. The frequency behaviour of the tested configurations shows a similar dependence with the same maximum attenuation of 0.05–0.1 dB cm^{-1} in the frequency range of single mode propagation.

We can arrive at the very important conclusion that the insertion loss of the textile lines is not determined by the dielectric and ohmic losses, but by the reflections along the line in the lower frequency range and coupling to the parasitic modes at higher frequencies above the half wavelength. Although the textile wires feature high conductivity, this plays a minor role in determining the loss factor of the lines. The *XY* configurations show slightly lower losses in the single mode propagation range and weaker but more irregular coupling to odd modes. This is the effect of the orthogonal wires, which are able to destroy the constructive resonances of the odd modes to some extent.

Based on different measured line configurations we can conclude that the longest possible line length is equal to the half wavelength of the lines at the maximal desired frequency of usage. This allows the lines to be 10 cm long for maximal frequencies of approximately 1.2 GHz and 1 GHz for the *X* and *XY* configurations, respectively. For 100 MHz signals the allowable line lengths are tenfold and are in the range of 100 cm.



9.13 Far-end crosstalk measured on 20 cm matched load lines with and without shielding.

Signal integrity and crosstalk

Figure 9.12 shows a 100 MHz clock signal measured at the end of 20 cm textile transmission lines in different configurations, and demonstrates the signal integrity.

Figure 9.13 presents the results of the far-end crosstalk for the two neighbouring lines in GS and GSG configurations. The measurements were performed on two 20 cm-long lines terminated in a matched load. The amplitude of the aggressor signal was 2.5 V with a rise time of 6 ns. The ground fibre between the neighbouring lines in the GSG configuration, acting as a shield, was able to reduce the crosstalk from 7.2% in GS configuration down to 2.8%.

9.5 Conclusions

We have presented, for the first time, an extensive characterisation of textile transmission lines for use in wearable computing applications. The proposed textiles are fabrics with conductive fibres in one or both directions and with different yarn fineness. This variety of fabrics opens a wide range of possible transmission line topologies, allowing a configuration to be found that fits the target application.

The FR4 interposer with coplanar solder pads and SMA connectors allowed the textile samples to be reliably connected to the measurement equipment. The TDR measurements showed that the achievable characteristic impedances lie between 120 Ω and 320 Ω. To study the influence of fabrication tolerances, the textiles were modelled with Sonnet, an electromagnetic field simulation tool. The simulation results showed that, with the given geometry variations, an accuracy of ±5% to ±10% for the characteristic impedances is achievable.

High frequency network analyser measurements were performed up to 6 GHz. The extracted frequency characteristics revealed that the dielectric and ohmic losses do not determine the line insertion loss. The line insertion loss is mainly influenced by non-uniform impedance profiles along the lines up to the half wavelength and by coupling to parasitic modes above this frequency point. This results in cut-off frequencies of 1.2 and 1 GHz for 10 cm-long lines in *X* and *XY* configurations, respectively. Good signal transmission for a 100 MHz clock signal was proved through 20 cm textile lines. Experiments also showed that grounded conductor lines between two neighbouring signal lines reduced crosstalk from 7.2 to 2.8%.

The final conclusion of this work is that conductive textiles provide much more than EMI shielding and power supply. Transmission lines with controlled characteristic impedance and high signal integrity up to several 100 MHz enable new options in interconnection for wearable computers.

9.6 Future challenges

To advance from electronic textiles to electronic clothing, research has to be carried out in the following areas:

- clothing technology for manufacturing
- testing under wearing conditions and washing/cleaning treatments
- investigation of reliability.

Electronic textiles have to maintain their functionality through repeated wear and washing cycles. They must not be damaged by constant motion and stress from body movements, perspiration and body heat. At ETH Zurich wearing stress is investigated in order to develop a ‘body map’ showing the stresses on different parts of the clothing during wear processes. Furthermore, the acceptability of these garments will depend on how comfortable they are. The garments have to support the wearer’s thermoregulation and should also be friendly to the skin. The electromagnetic fields emitted by electronic systems in clothing have to be investigated and possible ways have to be found to reduce the effects on the environment and the user. Last but not least, clothing concepts have to be developed. Depending on the application, electronic functionality can be fully integrated or a modular approach can be chosen, where clothing provides a kind of ‘platform’ for several possible modules. In order to achieve these objectives, close interdisciplinary cooperation in the fields of electrical, textile and clothing technology is necessary.

9.7 References

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