Ambient Intelligence Visions and Achievements: Linking Abstract Ideas to Real-World Concepts

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Abstract

The Ambient Intelligence vision is abstract and as such not useful for funding decisions, research project definition, and business plan development. This is in particular the case for the electronic design community. The European Commission intends for the EU to achieve world leadership in Information Societies technologies within ten years. To that end, it has incorporated the Ambient Intelligence vision in its Sixth Framework. Microelectronics and nano- and optical devices are seen as key technologies. Interesting chip-level challenges are found in, amongst others, explicit modeling of mobility and self-management, and novel computing substrates, based on electronic textiles or organic electronics.

1. Introduction

Ambient Intelligence (AmI) is the vision that technology will become invisible, embedded in our natural surroundings, present whenever we need it, enabled by simple and effortless interactions, attuned to all our senses, adaptive to users and context and autonomously acting. High quality information and content must be available to any user, anywhere, at any time, and on any device.

This vision is abstract and as such not useful for funding decisions, research project definition, and business plan development. This is in particular the case for the electronic design community. There is a large difference in abstraction level between the thinking about Ambient Intelligence systems and the micro-, nano-, and optoelectronic components, needed to implement those systems. Indeed, it is very important to bridge those levels of abstraction, because after all, it's those components that provide the options for future developments in the Information Society realm. On the one hand, Ambient Intelligence is such a wide field that almost any technological development can be situated somewhere in the complex structure of required technologies. On the other hand, one should be cautious not to view developments in isolation, since the examples of ineffective local maxima are abundant.

This article is a reflection of the Special Session on *Ambient Intelligence Visions and Achievements* of DATE-03. It brings together the European Union's view on Ambient Intelligence, as stipulated in its Sixth Framework, with some technological developments that are seen as drivers of future component technologies. Particularly the link with electronic design is being explored.

For true Ambient Intelligence to become a reality, it should completely envelope humans, without constraining them. Distributed embedded systems for AmI are going to change the way we design embedded systems, in general, as well as the way we think about such systems. But, more importantly, they will have a great impact on the way we live. Applications ranging from safe driving systems, smart buildings and home security, smart fabrics or e-textiles, to manufacturing systems and rescue and recovery operations in hostile environments, are poised to become part of society and human lives. Technology advances already show that embedding logic in textiles is possible in the next 3-4 years, while foldable plastic displays and tags have already been shown to work, and molecular transistors pave the way for nano-logic designs that could inconspicuously be sprinkled onto smart surfaces or environments. After elaborating the European Commission's vision on AmI, we touch upon the emerging technologies of electronic textiles and

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organic (plastic) electronics. We end this paper with the challenges in managing the highly dynamic emerging AmI environment.

2 European Community Research in Information Society Technologies

2.1 The vision

In 2001, the Information Society Technologies Advisory Group (ISTAG) proposed a longer-term perspective in preparation of the next European Community Framework Programme for Research and Technological Development [7]. With the help of experts from across Europe, a vision was elaborated describing what living with ’Ambient Intelligence’ might be like for ordinary people in 2010.

The vision was shaped through a set of scenarios in which people (not just ’users’, ’consumers’ or ’employees’) are at the forefront of the Information Society. Besides addressing the critical socio-political factors required for the eventual societal acceptance, and the business and industrial models likely to make a successful business case, the vision also identified a number of key technological requirements that would be instrumental in making it all happen: (1) very unobtrusive hardware, (2) a seamless mobile/fixed communications infrastructure, (3) dynamic and massively distributed device networks, (4) natural feeling human interfaces and (5) dependability and security. Those technology requirements were also put on a timeline identifying the main technological roadblocks and potential break points during this 10 year timeframe.

2.2 The Framework Programme

The 6th Framework Programme (FP6) is the Union’s main instrument for the funding of research in Europe.

Seven key areas for the advancement of knowledge and technological progress within FP6 have been chosen: genomics and biotechnology for health; information society technologies; nanotechnologies and nanosciences; aeronautics and space; food safety; sustainable development; and economic and social sciences.

The main focus of FP6 is the creation of a European Research Area as a vision for the future of research in Europe. It aims at scientific excellence, improved competitiveness and innovation through the promotion of increased co-operation, greater complementarity and improved co-ordination between relevant actors, at all levels.

The specific programme aiming at integrating European research (the largest component of FP6) defines Information Society Technologies (IST) as a thematic priority with the objective to ensure European leadership in the generic and applied technologies at the heart of the knowledge society.

FP6 will cover the time horizon 2003-2006. It matches with the ISTAG timeline as the last actions to be launched in 2006 are likely to terminate around 2010, delivering by then the technologies underpinning the AmI scenarios. Therefore, the focus of IST in FP6 is on the future generation of technologies in which computers and networks will be integrated into the everyday environment, rendering accessible a multitude of services and applications through easy-to-use human interfaces.

2.3 The challenges

The ability to develop such advanced products and services increasingly depends on excellence in designing and producing the basic building blocks of the Information Society technologies, namely microelectronic, optoelectronic and microsystem components. R&D in those areas is leading to ever-growing levels of device and function integration at component level. On the one hand, this integration is leading to the absorption of increasing numbers of functions in the components so that a system is built with ever fewer components. On the other hand, it means that an increasing number of different functions such as logic, memory, I/O, analog, RF, sensors, and software, need to be integrated on a single component, thereby raising the complexity of their design and manufacturing.

The embedding of computing and networking capabilities into more and more objects and environments, as can be anticipated from the AmI vision, results in distributed and real-time forms of computation that place new and severe demands onto micro-/optoelectronic devices in terms of functionality, design, power, robustness, wireless communication, packaging, and also cost.

More than ever, micro-/optoelectronics will have to increasingly integrate application know-how. It is important for European application system producers to forge alliances with trusted partners for the integration of components, and to ensure that an important part of the innovation, added value and high-quality jobs remain and are developed in Europe.

More mobility, less energy consumption, more performance, smaller size and weight, lower cost, high reliability, more flexibility and ubiquity have up to now been achieved with further downscaling (miniaturisation). However, we are reaching a stage of development where further scaling will create opposite effects such as growing energy consumption in standby mode and performance restrictions in active mode. Therefore, further pushing of existing technology limits also demands completely new solutions in micro-/optoelectronics in order for Europe to capitalise on the opportunities offered by mastering the enabling technologies of the Information Society. As an example, the theme of very low power electronics would bring together specific research topics such as low voltage device architectures, multi-voltage Intellectual-Property (IP) blocks, asynchronous design, low power manufacturing technologies.

At the nano-scale level, overall progress can only be achieved if new devices can be designed, manufactured and integrated into overall system architectures. This requires increasingly rare interdisciplinary expertise, i.e. the contribution of many areas of science and techniques. This will be a major challenge in the realisation of the AmI landscape.

3 Integrated Microelectronics in Smart Textiles: Wearable Electronics

The world of electronics is nowadays centred on “devices”. Personal computers, home cinema systems, cellular phones and alike are pieces of equipment able to offer us services: computation, information, entertainment, and communication. The development of electronic devices as we know them has been following the path of adding performance and complexity. The technology of electronics has been following the same path, growing on an exponential increase of integration in time (Moore’s law), which results in a rapid increase in speed, performance and complexity.

The AmI vision suggests a different way for electronics to exist in our world. In the AmI model electronics has to be pervasive, embedded, easy to access and able to interoperate autonomously. To gain these attributes electronics will have to leave the exclusive domain of objects recognised as “electronic devices” and become also part of the ambient, of each object. There are several ways of achieving this result.

An approach is to proceed on the way of miniaturisation, producing electronic systems that are able to sense the environment, interact with people, communicate with other electronic systems, and still that are so small, cheap and power efficient that they can be attached to any possible object or dispersed in the ambient. The “smart dust” concept is an example of such an approach [25]. Another possibility is to conceive ways of integrating the electronics in traditionally “non electronic” objects, like, for instance, clothing.

For integration into everday’s clothing, electronic components should be designed in a functional, unobstrusive, robust, small, and inexpensive way [8, 21]. With the ongoing progress of miniaturization in microelectronics, a number of entertainment, safety, communciations, and health care applications for ’wearable electronics’ can be exploited using off-the-shelf chip systems today.

The implementation of microelectronic components into clothes and textile structures has been demonstrated through a speech-controlled MP3 player system [14]. Attention has been paid to achieve compatibility between electronics and textile design.

The demonstrated interconnect and packaging technology uses polyester narrow fabrics. Several warp threads of this fabric include approximately 50 microns thick copper wires which are coated with silver and polyester. The electrical isolation of the wires is first locally removed by laser treatment. Then a thin flexible circuit board with structured electrodes is glued and soldered to the textile structure.

A miniaturized module containing the MP3 player electronics (audio module) is interconnected with an electrically conductive polyester fabric via a flexible circuit board connector. The complete unit is molded forming a water-proof and mechanically robust casing.

Figure 1 gives an overview of the MP3 demonstrator system and its integration into clothing. A detachable module containing a rechargeable Li-Ion battery for power supply of the system and a Multimedia Card for data storage is connected to the audio module via a Serial Peripheral Bus (SPI) bus by means of the textile interconnect technology. Furthermore, earphones, the microphone for speech input, and a capacitive keypad module are directly connected and integrated into the clothing

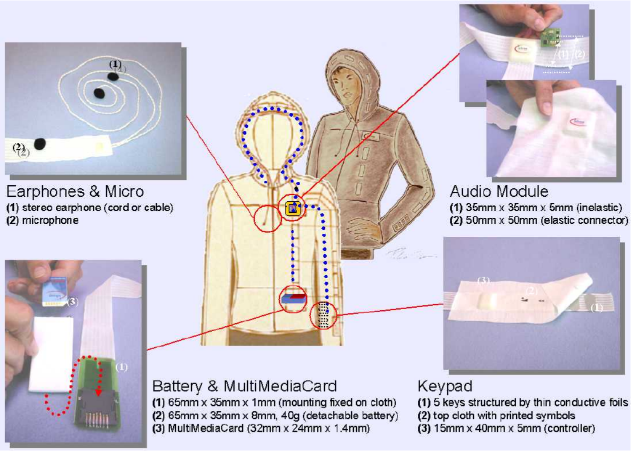

Figure 1. The textile wiring of the voice controlled MP3 player system is realized by polyester fabrics with interwoven thin copper wires.

An overview on the technical schematic and software for this architecture is depicted in Figure 2 [1]. The core chip in the audio module is based on an 8-bit 8051 microcontroller and 16-bit OAK DSP architecture, giving sufficient performance for applications like speaker independent voice recognition and MP3 decoding at a reasonable chip complexity.

The proposed system is expandable by further modules, such as wireless data transceivers and a variety of sensor devices. Since the power supply is crucial for all wearable systems, for specific low-energy applications the generation of electrical power from body heat has been demonstrated in [18] as a possible solution. Using a standard silicon MEMS technology, a thermogenerator with 16.000 thermocouples on a 7mm^2 chip has been realized. For a tempera-

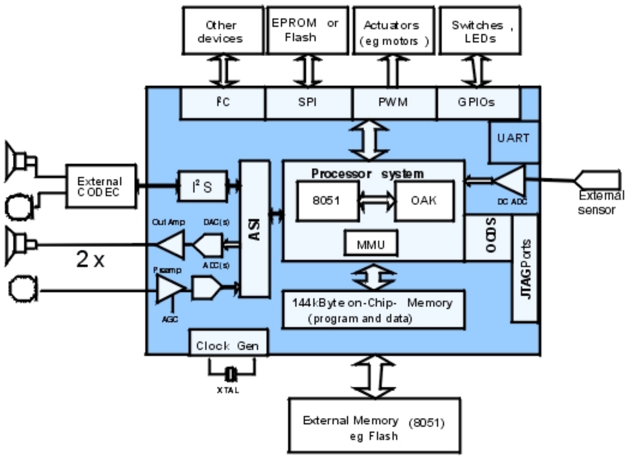

Figure 2. Architecture of the speech-controlled MP3 player application. [1]

ture difference of 5K across the chip an output power of 1.6 $\mu\mathrm{W}/\mathrm{cm}^2$ is obtained which is sufficient to power devices like a wrist watch.

In the future, mechanically flexible and inexpensive integrated plastic electronics are likely to play an important role in wearable systems, cf. the following section. In the context of the AmI vision, the manifold of new possible applications shows that smart clothes are a prime example of the convergence of various existing technologies enabling new solutions.

4 The Possible Role of Organic Electronics in the Ambient Intelligence World

Still more ways of “embedding” electronics in our environment could become feasible if the technology of electronics would loose its focus on ”wafers” and ”chips” to become compatible with the objects we use each day. If, for instance, one could produce at low cost on thin, flexible substrates electronic and opto-electronic devices, computational electronics, radios and displays could be glued on common objects without any need for higher integration. Possibly, the object itself (a package or a book for instance) could become the substrate for the electronics and we could print electronics as nowadays we print letters. Organic electronics promises to enable these developments.

Organic electronics is a new technology where organic materials (similar to the common plastic) are used as conductors and/or semiconductors to build electronic and opto-electronic devices. This new discipline started with the discovery of conductive polymers in 1977 [5] and with the early studies on the semi-conductive and electroluminescent [3] properties of the so-called “conjugated” organic materials. At the state of the art it is possible to make with organic materials bright light-emissive diodes [9] in all colours, transistors with performance comparable with amorphous silicon (mobility around 1 cm^2/Vs [24]) and solar cells with 2.5% power efficiency [23]. All these devices are manufactured depositing and patterning thin films of organic conductors, insulators and /or semi-conductors. Organic films can be deposited in vacuum, but also inexpensively from solutions [10, 17, 11, 16] or via high-resolution ink-jet printing [2]. Processing temperature is always low ($< 200^\circ\mathrm{C}$) so that organic devices can be manufactured on cheap, thin and flexible plastic substrates, obtaining flexible electronics. Organic transistors have sufficient performance to manufacture cheap digital electronics with a complexity, at the state of the art, of around 1000 transistors [12, 6]. The deposition processes are also compatible with large areas, which means, for instance, that organic transistors can be used to address the pixels of a display in an active matrix arrangement [19, 13]. Large, possibly flexible displays based on organic materials are presently in the focus of several research groups and could become a challenge to current rigid, amorphous silicon based, LCD screens.

Identification tags are very cheap code generators that are energized by an external field and can radio-transmit a unique code, identifying the items to which they are attached. These labels and wearable electronics, as discussed in the previous section, are other applications in which organic electronics could be exploited at the short term as a potential solution for large area, flexible, low cost, and maybe ubiquitous electronics.

Despite what has been achieved, within organic electronics there is still a complex challenge in improving lifetime, speed, and circuit complexity. But it also an interesting research object for other disciplines in electronics. The specific characteristics of organic transistors (only p-type, normally on devices) require the attention of modelling experts and circuit designers to create electronics with sufficient performance and yield [4]. The influence of mechanical stress on electronics produced on flexible substrates needs to be understood and modelled. The integration of these low-cost, ubiquitous pieces of electronics with the other components of an AmI world will create a serious challenge to system design. An analysis of such problems is presented in the next section.

5 Mobility and Self-Management of Ambient Intelligence

The integration of computing devices into everyday environments has been an object of research for several decades. As device technologies improve, devices become smaller and cheaper, it is possible to envision, and perhaps even build, new substrates for computing [6]. These platforms will take advantage of the possibility of employing large numbers of physically minute devices, and permit their deep embedding into environments. For instance, regular fabrics and large plastic sheets can be used to turn windows into big TVs. Indeed, both plastics and yarns could provide inconspicuous computing power for a variety of applications.

Instead of today's rigid programming paradigm - design, build, and run - intelligent ambients offer a defect-tolerant programming paradigm where system behavior monitoring is interleaved with application (re-)mapping and architecture (re-)configuring. In such smart spaces, computational elements are inconspicuously embedded into their environment, while offering a wide area network for increased defect-tolerant computational power. For instance, in the context of e-textiles mentioned in Section 3, redundant filaments and routing paths would bypass fabric-specific defects, thus offering almost seamless operation under hostile or unreliable conditions [15]. From wearable audio to mobile phones and personal healthcare the trend is towards the portability and softening of conventional plastic information devices (e.g. cell phones, PDAs, etc.). As shown in sections 3 and 4, these new computing substrates provide opportunities for new user interfaces that can also appear and function like everyday accessories.

Although intelligent ambients ostensibly present distributive computing challenges similar to those currently being pursued in pervasive computing research [22], the specific characteristics and demands of the info-computing environment add new dimensions. Specifically, since such systems will be composed of highly unreliable, low cost, and simple components and interconnects, the desire to achieve an overall robust system will require exploiting ultra redundant and distributed component networks. Compared to other real-life applications (e.g. data networks, desktop multimedia), the following issues are critical for the class of applications that we envision:

- limited energy, processing capabilities and buffering space per computational node
- failure mechanisms that may affect both computational nodes and communication links
- highly spatially correlated node and/or link failures due to topological placement
- highly temporally correlated node and/or link failures due to external events (such as temperature or environmental changes)
- the need for scalability and flexibility of resource management, as well as local vs. global management tradeoffs.

As such, intelligent ambients pose unique challenges as opposed to classic embedded systems, distributed or not. First, *abstract specification* of desired system characteristics has to allow for dynamic changes in the application software partitioning and (re-)mapping on the hardware platform. In fact, we believe that some of the decisions related to application (re-)mapping and communication have to be completely moved at run-time. While the initial mapping of the application onto the platform can reflect a particular set of constraints, these may be changed on-the-fly, depending on the operating conditions. Second, *adaptability* to changes in the communication topology and/or underlying architecture, as well as environment or operating condition changes have to be explicitly modeled (e.g., finite battery lifetime or non-zero failure probabilities) [26]. Such challenges, naturally require a new computation model able to unify the application and architecture characterization in terms of localized computation and loose inter-particle communication where many, unreliable components communicate infrequently one to another [20].

From an implementation perspective, we believe that *energy*, *fault-tolerance* and *mobility* are the three key concepts that deserve special attention when designing smart ambients. While energy and fault-tolerance are concepts more familiar to the computer systems community, mobility is a newly added dimension which sits at the very heart of the pervasive computing environments that we are bound to build in the near future. Indeed, for such a heterogeneous distributed system, nodes may join or leave the network at any moment and then becoming unreachable due to users' mobility, energy sources depletion, intermittent failures, etc. Consequently, designing embedded systems for such environments characterized by high volatility of the network topology is going to be very different compared to standard practice in digital design. To this end, we believe that specification, modeling and analysis of such systems will become possible only by using a *mobility-based calculus* where the emphasis should be put not only on modeling the limited resources (power, memory, etc.) that usually characterize the class of portable devices, but also on the communication properties, seen as a dynamic phenomenon, that enables individual nodes in the network to interact, move around and collectively perform a given task. Finding ways to partition and distribute complex tasks, in a scalable manner, among computational nodes with limited resources represents perhaps one of the most challenging problems that need to be solved in order to seamlessly integrate computers into ambients.

In summary, what is needed, is the availability of sufficiently complex instances of emerging technologies (e.g. organic electronics) and a set of methodologies and tools that will be able to provide for AmI systems what modern design flows have provided for classic digital integrated systems. Irrespective of the underlying computing substrate, this research area is still in its infancy, without much support from existing methodologies and tools.

6 Conclusions

Ambient Intelligence is part of the European Union's vision on the Information Society. However, its social benefits cannot be realized unless a number of requirements regarding mixed-technology design have been met. This involves seemless integration of nano- and opto-electronics. It also involves electronics becoming inconspicuous, by being incorporated within more natural user interfaces or even consisting of new computing substrates (e.g. fabrics and plastic). Design methodologies and tooling for these devices, the software running on them, and the underlying communication architecture will have to be based on new paradigms that take the highly dynamic AmI environment into account. This means that dynamic application mapping (self-management) at every level will have to ensure proper load and network balancing, based on accurate models, not only of processing performance, power consumption and network bandwidth, but also for energy sources, mobility and quality of service.

References

[1] B. Burchard, S. Jung, A. Ullsperger, and W. Hartmann. Devices, software, their applications and requirements for wearable electronics. *ICCE*, pages 224–225, 2001.

[2] S. Burns, C. Kuhn, N. Stone, D. Wilson, A. Arias, T. Brown, P. Cain, P. Devine, K. Jacobs, N. Murton, J. MacKenzie, J. Mills, and H. Sirringhaus. Ink-jet printed polymer thin film transistors for active-matrix applications. *SID 02 Digest*, pages 1193–1195, 2002.

[3] J. Burroughes, D. Bradley, A. Brown, R. Marks, K. Mackay, R. Friend, P. Burns, and A. Holmes. Light emitting diodes based on conjugated polymers. *Nature, Vol. 347 (11)*, pages 539–41, October 1990.

[4] E. Cantatore, C. Hart, M. Digioia, G. Gelinck, T. Geuns, H. Huitema, L. Schrijnemakers, E. van Veenendaal, and D. de Leeuw. Circuit yield of organic integrated electronics. *To be published in ISSCC 2003 Digest of Technical Papers*, 2003.

[5] C. Chiang, C. Fincher, Y. Park, A. Heeger, H. Shirakawa, E. Louis, S. Gau, and A. MacDiarmid. Electrical conductivity in doped polyacetylene. *Physical Review Letters (USA), Vol.39, No. 17*, pages 1098–101, October 1977.

[6] B. Crone, A. Dodabalapur, Y. Lin, R. Filas, Z. Bao, A. LaDuca, R. Sarpeshkar, H. Katz, and W. Li. Large-scale complementary integrated circuits based on organic transistors. *Nature, Vol. 403, No. 6769*, pages 521–3, February 2000.

[7] E. C. I. S. Directorate-General. ISTAG report: Scenarios for ambient intelligence in 2010. 2001.

[8] S. Ditlea. The PC goes ready to wear. *IEEE spectrum*, pages 35–39, October 2000.

[9] R. Friend, J. Burroughes, and T. Shimoda. Polymer diodes. *Physics world, Vol. 12*, pages 35–40, June 1999.

[10] G. Gelinck, T. Geuns, and D. de Leeuw. High performance all-polymer integrated circuits. *Applied Physics Letters, Vol. 77, No. 10*, pages 1487–1489, September 2000.

[11] M. Halik, H. Klauk, U. Zschieschang, T. Kriem, G. Schmid, W. Radlik, and K. Wussow. Fully patterned all-organic thin film transistors. *Applied Physics Letters, Vol. 81, No. 2*, pages 289–291, July 2002.

[12] C. Hart, D. de Leeuw, M. Matters, P. Herwig, C. Mutsaerts, and C. Drury. Low cost all-polymer integrated circuits. *Proceedings of the ESSCIRC 98*, pages 30–34, September 1998.

[13] H. Huitema, G. Gelinck, J. van der Putten, K. Kuik, C. Hart, E. Cantatore, P. Herwig, A. van Breemen, and D. de Leeuw. Plastic transistors in active-matrix displays. *Nature, Vol. 414, No. 6864*, page 599, December 2001.

[14] S. Jung, C. Lauterbach, and W. Weber. A digital music player tailored for smart textiles: First results. *Avantex Symposium, Frankfurt, Germany*, 2002.

[15] T. Kirstein, D. Cottet, J. Grzyb, and G. Troester. Textiles for signal transmission in wearables. *Proc. ACM of First Workshop on Electronic Textiles (MAMSET 2002), San Jose, CA*, October 2002.

[16] H. Klauk, M. Halik, U. Zschieschang, G. Schmid, W. Radlik, R. Brederlow, S. Briole, C. Pacha, R. Thewes, and W. Weber. Polymer gate dielectric pentacene tfts and circuits on flexible substrates. *International Electron Devices Meeting Technical Digest*, 2002.

[17] H. Klauk, M. Halik, U. Zschieschang, G. Schmid, W. Radlik, and W. Weber. High-mobility polymer gate dielectric pentacene thin film transistors. *Journal of Applied Physics, Vol. 92, No. 9*, pages 5259–5263, November 2002.

[18] C. Lauterbach, M. Strasser, S. Jung, and W. Weber. Smart clothes self-powered by body heat. *Avantex Symposium, Frankfurt, Germany*, 2002.

[19] P. Mach, S. Rodriguez, R. Nortrup, P.Wiltzius, and J. Rogers. Monolithically integrated flexible display of polymer-dispersed liquid crystal driven by rubber-stamped organic thin film transistors. *Applied Physics Letters, Vol. 78, No. 23*, pages 3592–94, June 2001.

[20] D. Marculescu, R. Marculescu, and P. K. Khosla. Challenges and opportunities in E-textile analysis, modeling and optimization. *Proc. ACM/IEEE Design Automation Conference, New Orleans, LA*, June 2002.

[21] Philips. *New Nomads - an Exploration of Wearable Electronics*. 010 Publishers, 2001.

[22] M. Satyanarayanan. Pervasive computing: Vision and challenges. *IEEE Personal Communications*, August 2001.

[23] S. Shaheen, C. Brabec, N. S. Sariciftci, F. Padinger, T. Fromherz, and J. Hummelen. 2.5% efficient organic plastic solar cells. *Applied Physics Letters, Vol. 78, No. 6*, pages 841–3, February 2001.

[24] C. Sheraw et al. Organic thin-film transistor-driven polymer-dispersed liquid crystal displays on flexible polymeric substrates. *Applied Physics Letters, Vol. 80, No. 6*, pages 1088–90, February 2002.

[25] B. Warneke, M. Last, L. B., and K. Pister. Smart dust: communicating with a cubic-millimeter computer. *IEEE Computer, Vol. 34, No. 1*, pages 44–51, January 2001.

[26] N. Zamora, P. Stanley-Marbell, R. Marculescu, and D. Marculescu. Pre-copying: An improved code migration technique for future fault-tolerant electronic textiles. *Proc. ACM of First Workshop on Electronic Textiles (MAMSET 2002), San Jose, CA*, October 2002.