IC Design Challenges for Ambient Intelligence

Emile Aarts and Raf Roovers
Philips Research Laboratories
Prof. Holstlaan 4, 5656AA Eindhoven, The Netherlands

Abstract

The vision of Ambient Intelligence opens a world of unprecedented experiences: the interaction of people with electronic devices is changed as contextual awareness, natural interfaces and ubiquitous availability of information are realized. We analyze the consequences of the ambient intelligence vision for electronic devices by mapping the involved technologies on a power-information graph. Based on the differences in power consumption, three types of devices are introduced: the autonomous or microWatt-node, the personal or milliWatt-node and the static or Watt-node. Ambient intelligent functions are realized by a network of these devices with the computing, communication and interface electronics realized in Silicon IC technologies. Three case studies highlight the IC design challenges involved, and show the variety of problems that have to be solved.

Ambient Intelligence

Ambient intelligence refers to electronic environments that are aware of and responsive to the presence of people [1]. Ambient intelligent systems consist of many distributed consumer devices that interact with users in a natural way. The concept builds on the early ideas of *ubiquitous computing* introduced by the late Marc Weiser [2] and anticipates a digital world in which electronic devices are the embedded parts of fine-grained distributed networks. An extensive overview of recent developments and challenges in this extremely interesting field of research is given by the research agenda compiled by the national Research Council [3].

MIT's *Oxygen* project [4] and IBM's effort on *pervasive computing* [5] are similar approaches addressing the issue of integration of networked devices into peoples' backgrounds. Ambient intelligence aims at taking the integration even one step further by realizing environments that are sensitive and responsive to the presence of people. The focus is on the user and his experience from a consumer electronics perspective, which introduces several new basic problems related to natural user interaction and context aware architectures supporting human centered information, communication, service, and entertainment. For a treatment of these novel distinguishing factors we refer to the book *The New Everyday* [6].

The technology of ambient intelligence builds on Moore's law and the observation that electronics have become so small and powerful that it can be integrated into every physical object. The business models of ambient intelligence follow the lines of the experience economy, introduced by Pine and Gilmore [7], who anticipate a new economy in which business will be based on the sales of experiences.

The introduction of ambient intelligence will have a tremendous impact on IC design, and planar technology development, which can lead to a paradigm shift in these worlds [8,9]. The impact on systems design might be even larger because of the high degree of hybridization and complexity of ambient intelligent systems. Below, we further elaborate on these issues, addressing the impact of ambient intelligence on the design of integrated devices.

Ambient Intelligent Environments

In an ambient intelligent environment, people are surrounded with networks of embedded intelligent devices that provide ubiquitous information, communication, services, and entertainment. Furthermore, the devices adapt themselves to users, and even anticipate their needs. Ambient intelligent environments present themselves quite differently compared to contemporary handheld or stationary electronic boxes and devices. Electronics will be integrated into clothing, furniture, cars, houses, offices, and public places, introducing the problem of developing new user interface concepts that allow natural interaction with these environments. A promising approach is the one in which users interact with their digital environments in the same way as they interact with each other. Reeves and Nass were the first to formulate this novel interaction equivalence, and they called it the *Media Equation* [10].

Ambient intelligence covers a whole world of underlying technologies used to process information: software, storage, displays, sensors, communication, and computing. To identify the different devices that are needed to realize ambient intelligent environments we first introduce a scenario that facilitates the elicitation of a number of ambient intelligent functions from which device requirements can be determined.

The new everyday [scenario]

Returning home late after a days work, Tom approaches the front door of his home where he is recognized by the 3D animated dog Bello that appears tail wagging on the door, which is also a flat display. After authentication the door alerts that it is open by changing its color. Tom enters the hall where he can see in a single glance on the ambient home flow management system that his daughter Kathy is out with friends, that there are a few new messages, and that the domestic robot Dusty is cleaning the living. Dusty approaches him when he enters the living, and through a single phrase he sends Dusty off to the kitchen to continue its work there. He walks to the interactive table and starts handling his messages through a combination of touch and speech control. One of the massages indicates that the shopping list composed by the intelligent larder needs confirmation before it is sent to the e-supermarket. It also lists a range of menus that can be cooked with the food that is currently in the larder. Another message tells him that the home information system has located the information he requested about affordable holiday cottages with sea views in Spain. A glow tag in the photo frame on the buffet indicates that Kathy, who in the mean time has been notified by her private mobile communicator that dad is home, wants to contact her dad when he is available. Tom asks the home communicator to contact Kathy, and after a few seconds her image appears on a display in the window screen. After a chat with Kathy Tom starts browsing in his personalized video systems using a mobile touch pad integrated into the armrest of his chair. After some time Tom decides to stop video browsing and calls for a nice view. The home information system then switches the window screens to display the life sunset at the beach of the Café del Mar and starts playing easy listening music.

Basic functions of ambient intelligence

The above scenario contains three basic ambient intelligent functions. Firstly, the environment is *contextual aware*, which means that there are sensors integrated into the environment which communicate events that can be combined to determine meaningful states and actions, like person identification, position detection, and query interpretation. Secondly, audio, video, and data can be streamed wirelessly to any access device present in the environment, thus enabling *ubiquitous wireless access* to information, communication, services, and entertainment. Thirdly, users in an ambient intelligent environment interact with their surrounding through natural modalities such as speech, gesture, and tactile movements, thus enabling *hands free interaction* with their environment.

These basic ambient intelligence functions not only apply to home environments; they also apply to other environments such as *mobile spaces*, i.e., car, bus, plane, and train, *public spaces*, i.e., office, shop, and hospital, and *private spaces*, i.e., clothing. They support a variety of human activities including work, security, healthcare, entertainment, and personal communications.

Basic devices for ambient intelligence

All devices that process information need energy to do so. Depending on the availability of energy resources in a device, the amount of information processing for a given technology is constrained. The availability of energy in a device is therefore the discriminating factor for the distribution of ambient intelligence functionality in a network of devices. The following three generic classes of devices are defined.

1. Autonomous devices that empower themselves autonomously over a full lifetime. They extract the required energy from the environment by scavenging light or electro-magnetic energy, mechanical energy from vibrations or from temperature differences by means of thermo-electric generator. Examples are all kinds of tags and sensors. These autonomously-empowered devices are called *microWatt nodes*.

2. Portable devices that use rechargeable batteries with typical autonomous operational times of a few hours, and standby time of several days. Examples are personal digital assistants, mobile phones, wireless monitors, portable, storage containers, and intelligent remote controls. These battery-powered devices are called *milliWatt nodes*.

3. Static devices that have quasi-unlimited energy resource, e.g., mains powered or combustion engine. Examples are large flat displays, recording devices, (home) servers, and large storage and computing devices. These net-empowered devices are called *Watt nodes*.

Examples of these device classes are already found today, but are not yet ambient intelligent because they are not part of an integrated intelligent network.

The energy availability as well as the power dissipation of a device is not constant over time: different operating modes are defined depending on the device activity and energy resources. Large variations in peak to average power dissipation are encountered. It is clear that for all types of devices the energy management is a key function as it determines the potential for information processing.

Information processing and power dissipation.

The power needed for information processing technologies has a major impact on the appearance of ambient intelligence in devices. It will largely influence the functions that are allocated in different types of devices and how the *intelligence stack* in the network is organized: the distribution of computation, storage, and intelligence over the devices in the system. To illustrate this impact, all hardware device technologies involved in ambient intelligence are combined in a single graph shown in Figure 1, where the x-axis represents power dissipation, and y-axis represents the information processing capacity, given by

- *bytes of memory* for storage,
- *displayed raw bit rate* for displays,
- *raw bit rate of captured information* for sensors,
- *communicated bit rate* for communication, and
- *operations per second* for computing.

The upper left area of the figure is rather empty, because the combination of high information processing capacity and low power is difficult to achieve. For some of the technologies, like communication and computing, the power scales about linearly with information processing capacity.

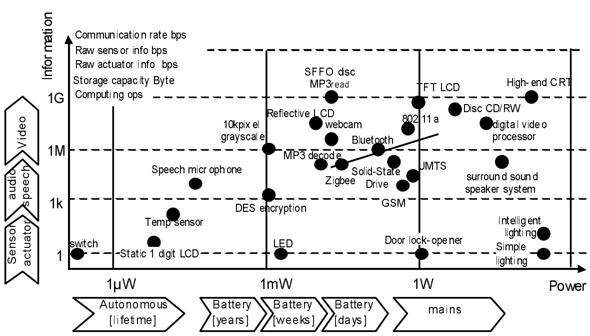

Figure 1. Technologies mapped on a power-information graph.

Based on this graph, the technologies that can be used in different node types are identified. Silicon IC technology can be used to implement computing, communication and interface electronics in all three devices types. The performance of IC technology spans orders of magnitudes, ranging from a few logic gates to GOPS for computing, from kb/s to Gb/s for communication and in interface electronics from pA, low bandwidth sensor signal to 100V high bandwidth signals in display drivers. This wide range of information processing capability of IC technology opens up opportunities for implementing ambient intelligence.

IC trends for computing

The IC technology roadmaps for computing are well described by the ITRS roadmaps [11]. Some of the trends are indicated in the graph shown in Figure 2. The continued device scaling of CMOS technology results in an further increasing availability of computational power

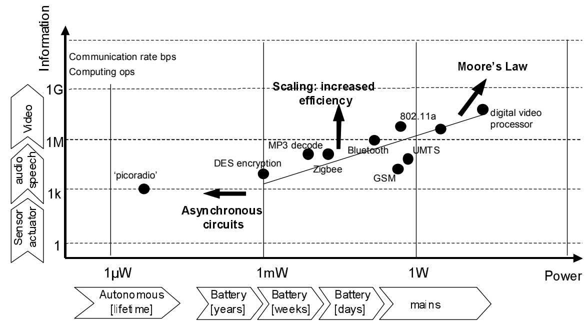

Figure 2. IC trends for computing.

As described by Moore's Law. This increased computational power is exploited in all kind of parallel architectures. The increased power efficiency of new technologies is particularly interesting for the battery-powered and autonomous devices but is countered by the increased leakage currents in these technology generations. For ultra low power asynchronous circuits are very attractive [12].

IC trends in communication

In communication circuits the quest for increased data rates hasn't stopped. However this is not the only trend that can be seen in Figure 3.

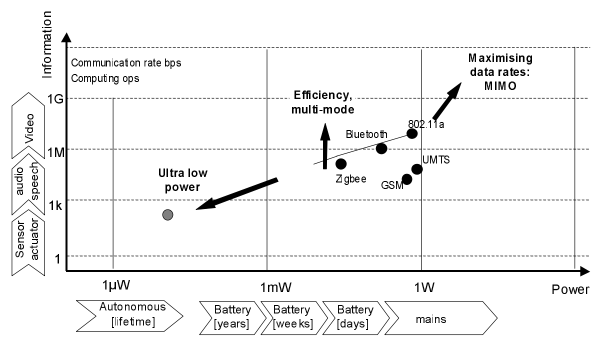

Figure 3. IC trends: communication.

New IC technologies provide options to increase the communication data rates: new spectrum at higher RF frequencies combined with new techniques like MIMO and space-time coding make Gb/s wireless communication feasible for consumer applications. However the energy efficiency of communication circuits scales different as for computing: the energy efficiency of communication (energy/bit) not only depends on the digital signal processing efficiency but also on the RF and mixed-signal processing. The power required for RF and mixed-signal circuits relates to noise and distortion parameters of devices and does not directly scale down with IC technologies. Nevertheless in milliWatt node devices the trends is towards increased efficiency and multi-mode, multi-standard capabilities. A relative new area is arising in the microWatt area, aiming for low data rate, low power communication.

Trends in interface electronics

The interface electronics follows closely the developments in sensor and actuator technology. The trends in interface electronics are indicated in Figure 4.

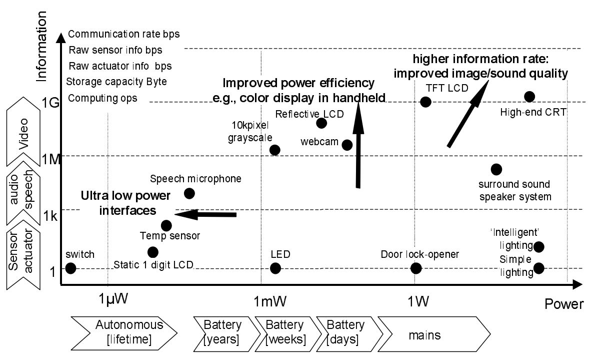

Figure 4. IC trends: Interface electronics.

Higher quality of audio and video input and output devices require more bandwidth and dynamic range from the interface electronics: amplifiers, filters, analog-to-digital and digital-to-analog converters. The power efficiency of these circuits becomes more important as low power high quality displays become available in battery-powered devices. Ultra low power sensor interfaces are needed for autonomous devices.

For interface electronics, dedicated devices are often required to handle high voltages and/or currents. These devices can be monolithically integrated with computing and communication electronics in dedicated IC technologies or as separate die combined in a multi-die package or module.

Architectures for ambient intelligence

Ambient intelligent environments are created by the interaction of many devices in a network. All these devices have a communication capability to realize the interaction and require digital computing to embed the intelligence stack. An ambient intelligence environment is shown in Figure 5 and is based on many networked devices of the three types.

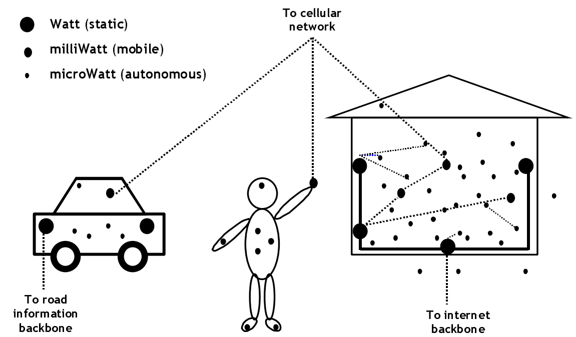

Figure 5. Ambient intelligent environments.

The amount of computing and communication that can be integrated in the different nodes is indicated in Figure 6. Due to power dissipation constraints, the maximum amount of communication is limited to kb/s in the microWatt node, Mb/s in the milliWatt node and Gb/s in the Watt node.

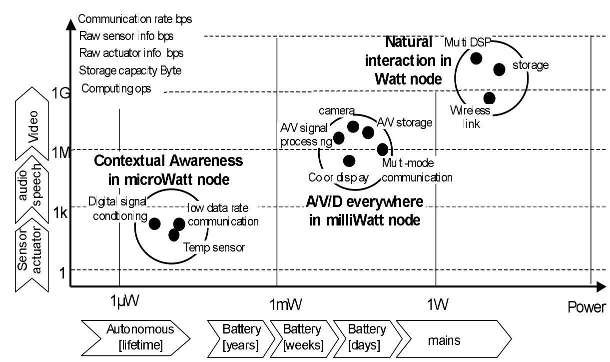

Figure 6. Clustering of technologies in devices.

This communication and computing network is extended with sensor and actuator technology to make ambient intelligence alive. The main question is: what technologies need to be added to these networked nodes to create an ambient intelligent home? How can awareness, information everywhere, and natural interfaces be implemented? This exercise will point towards the IC design challenges for ambient intelligence. For the indicated themes a possible distribution of functionality is shown in Table 1. Apart from technical feasibility other criteria are taken into account: the cost of devices, privacy and interoperability issues, size and design aspects, etc. Below we elaborate on the IC design challenges for three separate cases, indicated bold in Table 1.

Table 1. Ambient intelligence functionality distribution over micro-, milli- and Watt node.

	MicroWatt	MilliWatt	Watt
Awareness	**Gathering information from environment**	Accessing awareness information	Building awareness intelligence with information
Information everywhere	Data (e.g. smart label)	**A/V/data access, personal content management and storage**	A/V/data content management and storage
Natural interfaces	Interaction I/O	Interaction I/O	**Interaction intelligence**

Case studies: consequences on IC design

For each of the nodes a combination of communication, computing and sensor/actuator is made and the IC design challenges for ambient intelligence are shown.

Contextual awareness in the microWatt node

The functional block diagram for a microWatt node is illustrated in Figure 7. The awareness functionality is realised by combining a sensor with an mixed signal interface, digital signal conditioning and control functions, a wireless transceiver and an energy supply. Rabaey et al., have formulated various IC-design related research activities related to this field of research [13].

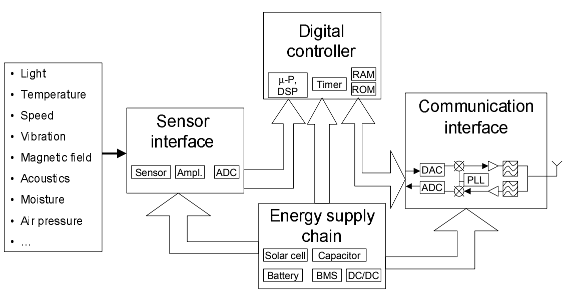

Figure 7. MicroWatt node for contextual awareness.

The design challenges for the microWatt node are on multiple levels. Although the complexity of a single device is rather low, the combination of various technologies with low power dissipation as a most important design criterion, is a challenging task, requiring:

- Accurate modeling of the various technologies e.g. power dissipation has to be characterized for all technologies, with very high accuracy over wide operating conditions, including lifetime degradation.
- Multi-technology device simulation: power optimization requires combined simulation of multi technologies probably on a very low abstraction level to achieve the highest power accuracy e.g. a combination of MEMS for sensor, solar cell, digital and RF technology.
- Network simulation: the combination of a large number of microwatt nodes in a network requires network modeling and simulation to study the effects of redundancy, defective nodes, protocol aspects, etc. of multi devices in network.

Information everywhere in the milliWatt node

The functional block diagram of a milliWatt device that realizes information everywhere is shown in Figure 8.

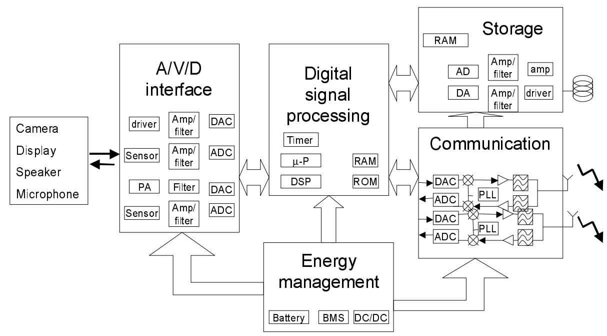

Figure 8. milliWatt node for information everywhere.

A multitude of wireless connections guarantees access to different types of information with different data rate and quality of service. Interface circuits are processing audio and video signals and a local storage device that adds functionality. Energy and battery management play an essential role in these devices. The design needs to be flexible as it has to cope with multi-standards and multi-modes, changing network environments and upgrading of the functionality during lifetime. The IC design challenges in this milliWatt node are:

- The flexibility/power trade-off: accurate power estimation of digital circuit and architecture implementations are needed to make optimal design choices.
- Integration of multi-mode/standards communication interfaces require low power mixed-signal and RF design tools.
- On system level a trade-off have to be made between the increased amount of compression of the A/V/data stream with related power dissipation and the reduced data rate of the communication link.

Natural interfaces in the Watt node

Figure 9 shows the Watt node for natural interfaces. The natural interfaces requires the extraction and of information from various information streams (audio and video signals) and setting up an intelligent dialogue with

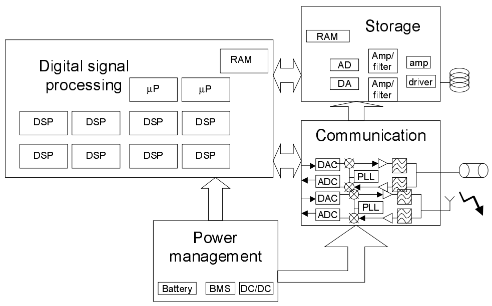

Figure 9. Watt node for natural interfaces.

the user. The information input streams are received from milliWatt nodes. The extraction of information from these data streams requires large amounts of memory e.g. content databases, language information, etc. This memory is provided by local storage combined with internet-like distributed storage. However the major IC content of these nodes will be the computational functionality needed for the intelligence stack: huge amounts of digital signal processing have to be organized to realize the natural interface functionality. This node will benefit the most from Moore's Law.

Below we mention some of the IC design challenges for the Wattnode; see also [14].

- IC design complexity management: integrating billions of transistors into a working IC. All design tools will have to deal with these giga-scale designs.
- Energy-flexibility trade-off: the designer has to make choices within the range from fully hard-wired to full programmable solutions, and needs tools that support to explore the resulting design space.
- Ensuring the system modularity: systems should be open to support addition and development of new system functionality.
- Architectural issues of the intelligence stack: the development of intelligent software components requires the introduction of adequate software interfaces that support distributed processing.
- Testability: modular test approaches are needed that support system test and evaluation based on test specifications of individual components.

These case studies illustrate the variety of IC design challenges that are found in ambient intelligent devices and the IC design tools needed to realize them.

Conclusions

Ambient Intelligence is presented as a vision for the future of consumer electronics. It is shown that within the ambient intelligence concept the energy resources are a main criterion in the design of devices resulting in three generic types: micro-, milli- and Watt nodes. For these devices, silicon IC is the basic technology for computing, communication and mixed-signal interfaces. Ambient intelligent functionality is mapped on a network of devices of the three types. This is applied for awareness, information everywhere and natural interfaces and results in three case studies indicating the various challenges for IC design. These challenges are very broad and range from low-level device modeling, over power estimation of digital architecture, to managing the complexity of gigascale IC solutions.

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