A Research Agenda Towards Zero-Power ICT

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1. Introduction

Societies reliance and use of Information Communications Technology (ICT) is increasing. It is estimated that 2% of all energy consumption is now the result of ICT use. The energy consumption and carbon dioxide emission from the expanding ICT use, however, is unsustainable and will impact heavily on future climate change. Methods are required to make ICT technology more energy efficient but also the development of new self-powered, energy-harvesting technologies that would enable micro- and nano-scale systems that consume Zero-Power through the harvesting of waste energy from the environment are also required. Autonomous sensors for temperature and pollution monitoring are also key for SMART metering to reduce energy consumption in domestic and industrial environments. Zero-Power autonomous sensors for healthcare applications have the potential to change the expensive reactive healthcare market to a cheaper and more effective point-of-care diagnostic system. Such healthcare sensors also have the potential to radically change the care of the elderly to a more sustainable and scalable automated monitoring rather than present expensive labour intensive methods.

In this chapter, a brief introduction is given on the challenges and possible solutions followed by an analysis on the technological and market impact as well as ethical and societal issues arising from the use of Zero-Power ICT solutions for reducing the energy required in new services and products.

2. Background

2.1. Energy efficient ICT

ICT has become a strategic sector in the world economy. Its impact on cultural and social development is already paramount and it will keep growing in the foreseeable future. State of the art ICT is presently based on digital devices whose functioning is currently dominated by power dissipated which produces heat. This is a major problem for a number of reasons:

1. *Economic and social reasons*. Energy efficient ICT, that is, operating ICT devices with reduced amount of energy, is presently considered an objective of extremely high economic relevance. According to the SMART 2020 [1] study, "the share of ICT on the worldwide energy consumption today is in the range of 2-5%. Given that the use of ICT will further increase and the overall energy consumption will hopefully decrease due to the help of ICT and other measures, it is expected that the share of ICT on the worldwide energy consumption will grow in the future. Carbon dioxide emissions from the use of ICT are therefore presently increasing. Hence, it becomes more and more important to consider and improve the energy efficiency of ICT. In the short term, it will be an obvious and practical solution to better exploit the potential of technologies that already exist or are currently in the making. On the long term, new and disruptive ideas will be needed" [2].
2. *Technological reasons*. In the last forty years the semiconductor industry has been driven by its ability to scale down the size of the CMOS Field Effect Transistor switches, the building blocks of present computing devices, and to increase computing capability density up to a point where the power dissipated in heat during computation has become a serious limitation. In fact, the power density in modern day chips is several tens of W/cm^2 which implies a surface hotter than high-power hot plates. According to the International Technology Roadmap of Semiconductors [3] the limits imposed by the physics of switch operation will be the roadblock for future scaling in the next 10-15 years. The limit on the minimum energy per switching is set at approximately $3\,k_BT\ln(2)$ (approx 10^{-20} J at room temperature) [4].

Power dissipated versus switching speed of devices have been characterized since the 1970s [5] by a linear scaling rule where micro-fabrication capabilities, through the replacement of bipolar transistors with CMOS, allowed the continuation of the exponential increase trend in information processing capability. This has been known as Moore's law. However, since 2004 the Nanoelectronics Research Initiative[1], a US based consortium of Semiconductor Industry Association companies, has launched a grand challenge to address the fundamental limits of the physics of switches. Such limits are mainly represented by the minimum energy and minimum time, required to operate a switch. With the present estimate of the minimum energy required in current CMOS technology (with the Field Effect Transistor channel scaled down

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[1] The Nanoelectronics Research Initiative (http://www.src.org/program/nri/) was formed in 2004 as a consortium of Semiconductor Industry Association (SIA) (www.siaonline.org) companies to manage a university-based research program as part of the Semiconductor Research Corporation (SRC) (www.src.org).

to 1.5 nm, switching speed of about 40 fs) the resulting power density for these switches at maximum packing density would be on the order of 1 MW/cm^2. This is comparable to the power density in a rocket nozzle and is orders of magnitude larger than what is presently technologically manageable. Thus the amount of energy dissipated through heat is presently the major roadblock for continuing the increase in computing performance.

3. *Scientific reasons*. Presently the main effort to overcome the technological limitations is aimed at cooling the chips by removing the heat produced during computation. Specific attention goes to the charge transport on one hand and on the other hand on reducing the voltage operating levels up to the point of not compromising the error rate due to voltage fluctuations. Such a strategy has produced some interesting results[2] however it is clearly coming to an end due to the unsustainable energy input requirement. There are attempts to look at the problem from a more fundamental point of view by addressing the basic mechanisms behind the heat production and the role of fluctuations arising by lowering the threshold voltages.

2.2. Micro- and nano-scale wireless sensors

MEMS (Micro Electro-Mechanical Systems) and NEMS (Nano Electro-Mechanical Systems) technology has made significant progress in the last ten years and a new potential in distributed sensing and actuating devices is now approaching the market. Deployment in Wireless Sensor Networks (WSN) has aroused a lot of interest both in academia and industry. There is an increasing demand for ambient intelligence devices, various kinds of sensor networks for safety and environmental monitoring and for monitoring of the health of humans and animals.

Nowadays, thanks to advances in MEMS technologies, it is feasible to fabricate cheap and small sensor nodes that have not only sensing, but also data processing and communicating capabilities. WSNs differ from traditional wireless networks by features like the number of nodes, constraints on energy consumption, computation and memory. Obviously these unique characteristics bring new challenges to the research activity. One of the advantages of wireless communication is the easiness in deploying the sensors without the need of wiring and fixed positioning, thus reducing installation and maintenance cost. Furthermore, in some hostile environment it is difficult or even impossible to physically connect the sensors; therefore wireless communication is the only feasible solution. Due to the heterogeneity of potential application for WSN specific objective and constraints have to be taken into account.

These devices all need distributed powering systems. Presently this means wired power-grids, batteries or RF-sources, however all these solutions present some drawbacks. Wiring is expensive, adds weight and is subject to high failure rates in devices subjected to repeated motion. Traditional batteries are not a viable solution to the powering of such devices mainly because they have to be replaced once exhausted and the cost of replacing the batteries is many orders of magnitude greater than the complete cost of the systems. Alternative solutions based on micro fuel cells and micro turbine generators are also not suitable. Both involve the use of

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[2] See e.g. the Aquasar computer installed on 2010 at the Swiss Federal Institute of Technology (ETH) Zurich.

chemical energy and require refuelling when their supplies are exhausted. Thus the goal of powering such devices with energy harvested from the ambient has been in recent years the subject of a great research effort.

If one can realize an energy harvester with a capacity to deliver power of 100 µW, it would open up a large number of applications. Also, the availability of this kind of power sources would boost the development of even lower power devices, leading to the vastness of autonomous nanoscale ICT systems for implants and in-vivo health monitoring, environmental warning and hazard preventing networks and for other safety measures. In a wider context, electronic devices currently account for 15% of household electricity consumption, but their share is rising rapidly, mainly due to growing demand in Africa and the developing world. Next to the need for more secure and greener energy supplies at a large scale, immediate action has to be taken to employ alternative energy sources and reduce power consumption in consumer electronics at all levels.

3. Matching problems with solutions

Improving energy efficiency in ICT and powering networks of small wireless sensors are two important fields of active research that sit on a common scientific background: the management of energy from the micro- and nano-scales to the system level in conjunction with the processing of information.

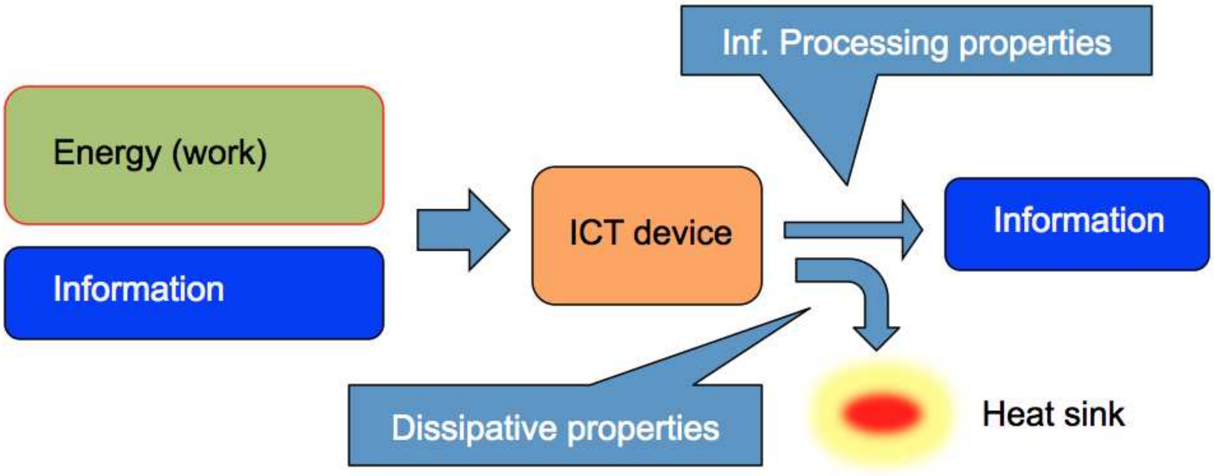

Figure 1. An ICT device is a machine that inputs information and energy (under the form of work), processes both and outputs information and energy (mostly under the form of heat).

Relevant scientific breakthroughs are needed on this topic for making progress in the two fields. Specifically, a new approach is required to the energy management of physical mechanisms at the nanoscale with the aim of setting the bases for a new thermodynamics of ICT devices. In this perspective an ICT device has to be considered as a machine that inputs information and energy (under the form of work), processes information and outputs information and energy (mostly under the form of heat). This is shown schematically in Figure 1. Energy efficiency is usually defined as “the percentage of energy input to a device that is consumed in useful work and not wasted as useless heat”. This definition, however, does not apply when we deal with processes at the nanoscale. Moreover the very basic mechanism behind energy dissipation requires a new definition when non-equilibrium processes involving only a few degrees of freedom are considered: the dream of highly efficient devices has to deal with a rethinking of both energy and information dissipation processes.

The long-term aim of research activities addressed here is to make possible low power ICT devices with a significant impact on energy efficiency on a much broader scale. Clearly, a new generation of energy efficient ICT devices has to deal with energy transformation processes at the nanoscale and allow for efficient power management of the realized system. This is undoubtedly a multidisciplinary task where competences from fields as diverse as physics, computer science, electronic engineering and mechanical engineering are brought together in a coordinated effort. This is evident in this remaining chapters of the volume where more technical details are presented. There are also a number of roadmaps towards providing Zero-Power technology for specific applications [6-10].

4. Standards and metrology

To enable comparison of different technologies, a key area that requires development is metrology for energy harvesting systems especially at the micro- and nano-scale. At present there are a lot of bold claims of energy harvesting devices that will save the planet and produce amounts of energy that defy the laws of physics. If consumers and markets are to have the belief and confidence in energy harvesting technologies to allow them to be implemented and used then standards and measurements that allow accurate comparison and benchmarking of the technologies are required.

The issues for metrology are that the input sources of energy come from a large range of sources. As discussed later in the volume the energy to be harvested can be in the form of kinetic, potential, electromagnetic, thermal or chemical energy and for ICT it will be converted into electrical energy. For each application, a different load impedance is likely and the electrical energy needs to be converted and impedance matched to the load. Standards are therefore required for a range of different potential applications to highlight the different areas of energy harvesting.

As an example, the efficiency of thermoelectric devices requires the accurate measurements of electrical conductivity and thermal conductivity. Thermal conductivity is already extremely difficult to measure in bulk systems with uncertainties of around 50% due to the difficulty of heat transport through any object that touches the item to be measured. As thermometers are required to measure the temperature, the act of measurement adds uncertainty to the measurement through the parasitic loss of heat. At the micro- and nano-scales, the measurement is far more complicated and difficult and new techniques and ideas are required. For vibrational energy harvesting the issues will be related to what frequency and bandwidth should be used to compare devices.

There is already a European Metrology Research Programme on energy harvesting technologies (http://www.emrp-metrology-for-energy-harvesting.blogspot.com/). The ZEROPOWER network (http://www.zero-power.eu/) has already discussed a number of collaborative projects on energy harvesting standards and it is clear for future energy harvesting that metrology and standards are at the core of providing robust and quantitative performance data for energy harvesting technologies.

5. Potential impact, applications and markets

The impact of realising low-power electronics in the energy budget is huge. As global energy demand increases, ICT and consumer electronics (CE) account for one of the fastest growing sectors regarding energy consumption. The International Energy Agency (IEA) projects that by 2030 the global energy use by just residential electronic gadgets could rise to 1,700TWh. This is around 40% of the generation capacity of the largest electricity producer in the world (USA). In fact, it would require at least a dozen power plants with 1-2GW output to accommodate this trend which if placed in a single location would make that country the third largest electricity producer. In the developed world, roughly one third of the annual electricity bill from residential ICT and CE is charged to computers, peripherals and other mobile devices; audio-visual equipment accounts for the other two third (estimates based on IEA data and an independent study by the Consumers Electronics Association-USA).

Even greater benefits may derive from new applications. The Smart 2020 study [1] indicates that “ICT’s largest influence will be by enabling energy efficiencies in other sectors, an opportunity that could deliver carbon savings five times larger than the total emissions from the entire ICT sector in 2020.” Indeed, miniaturised electronic systems applied in ambient intelligence, point-of-care diagnostics, chemical warfare security, logistics and supply-chain control can potentially achieve large cost/energy savings with additional huge societal impact.

The OECD Health Data show that an average of 8.9 % of GDP in developed countries is spent on healthcare costs. Over the last 50 years, healthcare spend has outpaced GDP growth by about 2 percentage points a year in most OECD countries and there are few signs that this trend will slow. Advances in e-Health, the healthcare practices supported by ICT, are a very promising route to reduce the bill. For example, point-of-care devices to diagnose Acute Coronary Syndrome can yield results around 1.0 to 1.5 hrs earlier than analysis in the central laboratory, allowing for earlier intervention or rule out to a step down unit. At a cost of €1,300-€6,500 per hour of emergency department bedtime, the shorter turnaround time provides major savings. In m-Health, mobile electronics and communication technologies are utilised to deliver solutions in prescription drugs monitoring and in remote diagnosis and even treatment for patients who do not have easy access to a physician. Based on ubiquitous intelligence from energy-efficient miniaturised sensors (e.g., in wearable/textile integration), remote health monitoring devices that track and report patients’ conditions are possible. Such

ICT solutions are urgently needed taking into account Europe's aging population and the even more demanding constraints on resources and patient empowerment. Current estimates on cost savings from m-Health for chronic diseases in OECD countries are valued at €227 - €273 billion. m-Health is already around a €2 billion market according to CSMG, and it is expected to grow over the next five years at a 25 percent CAGR (compound annual growth rate). A McKinsey&Company report estimates an untapped consumer-led market potential of up to several tens of billions Euros.

Estimates of the current WSN market, which is expected to grow rapidly, are at €1-2 billions. The market of energy harvesting ICT devices alone is estimated close to €1 billion in 2011, to grow to around €5.7 billion by 2021. This is based on "250 million sensors powered by an energy harvester (at an average price of $6 per harvester), and by then numerous consumer electronic devices including laptops, ebooks and cell phones" (IDTechEx Report). However, market fragmentation owing both to enabling technology and end-user application makes it very difficult to reveal the full potential of the market. The healthcare sector was mentioned above. Another short-term windfall impact is expected from applications in energy efficient buildings. For example, just the wireless-enabled HVAC sensors (heating, ventilation and air-conditioning) tapped into the building automation systems will have a market of €150 million and will result in multi-billion euro savings (estimates of 40%-50% energy savings have been reported).

The potential benefits from the research and development of low-power nanoelectronic components and autonomous sensors stretch out to many other research areas. Detailed knowledge of the dynamics of energy/information carriers and the realisation of appropriate channels is of paramount importance for Beyond Moore technologies. In the short-to-medium term, the required advances in energy management concepts, ranging from managing dissipation and fabricating thermodynamically efficient devices at the nanoscale to designing materials and circuits for more efficient electronics, will have diverse impact in metrology, nanofabrication, characterisation and modelling, materials research and smart grid applications.

6. Potential ethical and societal issues

A first general issue, inherent to the Zero-Power ICT concept, which will have a clear ethical and societal impact is related to the contribution of the ICT to climate change. It is nowadays well established that around 2% of the global emissions of carbon dioxide are due to the manufacture, use and disposal of ICT devices and systems. This percentage can increase to 3% in 2020 if the efficiency of ICT is not improved. Zero-Power technologies, including here the binomial **ultralow power electronics – energy harvesting strategies**, will have a double impact in this issue: from one hand they can stop the growth and even reduce the 2% contribution to CO_2 emissions, but on the other hand, they can help to enable the reduction of the remaining 98% of the total emissions produced by non-ICT actors. The main way that ICT will be used in improving energy efficiency is through adding smartness or intelligence to the functionalities/systems in which energy efficiency is required to be improved. Thus, new concepts such as **smart city**, **smart work**, **smart grid, intelligent transport** or smart/intelligent whatever will arise that require autonomous sensing systems that consume no power. Zero-Power technologies will have the opportunity to demonstrate their capabilities to provide smartness/ intelligence to all these functionalities/systems in an energy efficient way.

So, a first type of application will be focused in this so called "ICT for the energy efficiency improvement of ICT and non-ICT systems". In this class of applications we can include:

- Devices and systems for the improvement of energy distribution, consumption and management in general at home, industries and civil buildings and infrastructures. **Smart grid** concept and extensions of the concept to other kinds of energy as gas or renewables (solar, wind).
- Devices for the energy efficiency improvement of ICT systems and equipment: from tiny integrated microsystems to large data centres.

A second issue is related to the improvement the quality of life of the society. Although applications in the previous point have also an incidence on the population quality of life, this impact is expected to be plausible in a medium to long term. Here, a set of applications which have a short term, more direct impact to the quality of life are listed:

- Health related applications such as Body Area Networks (BAN) technologies for health monitoring of elderly, sick, disabled or newborn people.
- Animal tracking and monitoring such as WSN for remote control of position and vital constants of livestock.
- Ambient monitoring using WSN for pollution monitoring in big cities or industrial regions, for fire prevention in forests.
- Geo-atmospheric monitoring employing WSN for monitoring, prediction and prevention of natural catastrophes such as flooding, hurricanes, snow slides, earthquakes or tsunamis.
- Security improvement and accident prevention in cars where systems are already implemented in aircrafts that can minimize the probability of collision as well as detection of individual or collective behavioural patterns that can lead to a dangerous situation.
- Goods tracking with smart active RFID technologies for the improvement of manufacturing and distribution of goods at the industry and distributor level, but also for helping the user in quotidian buying and consuming activities.
- Circulation improvement of public and private transport in cities using smart navigation systems for dynamic calculation of efficient itineraries and smart parking search systems.

In general, energy harvesting and ultralow power electronics will act as enabling technologies in all previous applications. Thus, for instance, most of the previous applications are strongly connected to efficient wireless communication technologies and other related technologies such as **wireless sensor networks** (WSN). So, it is expected that WSN technology will not be deployed in real applications until both energy harvesting and low power electronics will provide good solutions for self-powering WSN nodes and for decreasing energy consumption of the sensing and communication functions respectively.

However, it is important to educate the public about the energy that ICT devices consume, the carbon dioxide that is produced from the use of ICT devices and how to reduce the energy and carbon dioxide emission from the use of ICT. Awareness of the new technologies that can help reduce both the energy consumption and carbon dioxide emission needs to be promoted. Energy harvesting is a developing research area and if it is to be taken up by society, it is important to educate society about the benefits of the new technology.

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