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SIGNIFICANCE OF NANOTECHNOLOGY FOR FUTURE WIRELESS DEVICES AND COMMUNICATIONS

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ABSTRACT

This paper reviews the expected wide and profound impact of nanotechnology for future wireless devices and communication technologies.

I. INTRODUCTION

One of the central visions of the wireless industry aims at ambient intelligence: computation and communication always available and ready to serve the user in an intelligent way. This requires that the devices are mobile. Mobile devices together with the intelligence that will be embedded in human environments – home, office, public places – will create a new platform that enables ubiquitous sensing, computing, and communication. Core requirements for this kind of ubiquitous ambient intelligence are that the devices are autonomous and robust. They can be deployed easily, and they survive without explicit management or care. As shown in Fig. 1, mobile devices will be the gateways to personally access ambient intelligence and needed information.

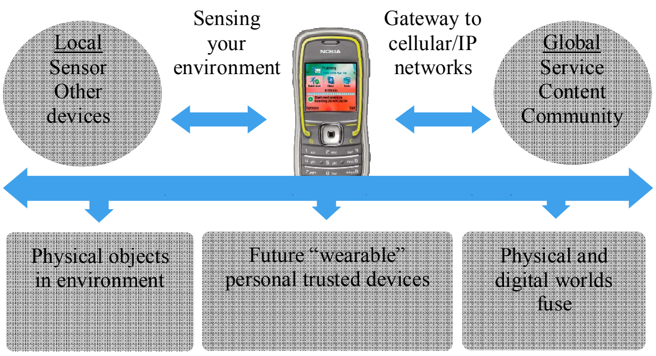

Figure 1: Mobile devices become gateways to ambient intelligence and needed information.

Mobility also implies limited size and restrictions on the power consumption. Seamless connectivity with other devices and fixed networks is a crucial enabler for ambient intelligence systems – this leads to requirements for increased data rates of the wireless links. Intelligence, sensing, context awareness, and increased data rates require more memory and computing power, which together with the size limitations leads to severe challenges in thermal management.

All these requirements combined lead to a situation which can not be resolved with current technologies. As we see in the rest of the paper and in other literature, nanotechnology could provide solutions for sensing, actuation, radio, embedding intelligence into the environment, power efficient computing, memory, energy sources, human–machine interaction, materials, mechanics, manufacturing, and environmental issues.

Nanotechnology is a field of science and technology of controlling matter on a scale between 1-100 nanometers. It is a highly multidisciplinary field, bringing together many fields, including electrical and mechanical engineering, physics, chemistry, and biosciences. Nanotechnology will radically affect all these disciplines and their application areas. Economic impact is foreseen to be comparable to information technology and telecom industries.

The vision of Nokia Research Center is to become the global leader of open innovation for human mobility systems of the fused physical and digital world, giving birth to the growth of business for Nokia. In this paper we will give an overview of how nanotechnology can help to realize this vision, and in particular what is the impact for wireless communication technologies.

II. SENSORS AND SENSING EVERYWHERE

Micromechanical sensors became an elementary part of automotive technologies in mid 1990, roughly ten years later more miniaturized micromechanical sensors are enabling novel features for consumer electronics and mobile devices. Within next ten years the development of truly embedded sensors based on nanostructures will become a part of our everyday intelligent environments.

Nanotechnologies may also augment the sensory skills of humans based on wearable or embedded sensors and the capabilities to aggregate this immense global sensory data into meaningful information for our everyday life. This requires novel technologies and cross-disciplinary research in many ways.

Embedding intelligent and autonomous devices into physical objects of the world requires that devices adapt to their environment and become a part of the network of devices surrounding them. There is no way to configure this kind of a huge system manually – top down. Nanotechnology can help to develop novel kind of intelligent devices where learning is one of the key characteristic properties of the system, similarly to biological systems which grow and adapt to the environment autonomously.

Nanotechnologies may open solutions for sensors that are robust in harsh environmental conditions and that are stable over long period of time. Today mechanical sensors – pressure and acceleration sensors – are already demonstrated to fulfil these requirements, but we do not have chemical or biochemical sensors that are stable or robust enough. Furthermore, the future embedded sensors need to be so inexpensive and ecologically sustainable that they can be used in very large numbers.

Driver for nanotechnologies in sensors is not primarily miniaturization. The size of the sensor depends on measurement itself, and the sensors need to be packaged in an

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appropriate way to integrate them with measurements. Nanotechnologies will enable new materials and new sensing elements for sensors. It will become possible to create sensors that consist of huge arrays of similar sensing elements and thus develop novel sensing principles for example for chemical and biochemical sensors.

III. SOLUTIONS FOR RADIO

RF operation in the GHz frequency range brings challenges not only with range and interference avoidance, but also with processing speed. The radio frequency determines the basic clock speeds and sets requirements on how often certain physical and medium access control layer signal processing algorithms need to be run per second. Here nanotechnology could help. For example, recent advances in nanotechnology and scaling allow building of systems with a large number of nanoscale resonators, e.g., NEMS devices [1], which could be used for GHz signal processing applications.

This type of a system can make spectral processing in RF domain feasible. This is of special importance for high data rate wireless communications systems. One particularly important application would be spectral sensing in mobile devices with flexible spectrum use and/or cognitive radio features. There wide radio spectrum bands need to be repeatedly scanned in real-time with low power consumption. In addition, a lot of processing speed and power is needed to analyze the data and run all the algorithms which enable intelligent use of spectrum and fast adaptation to dynamically changing radio environment. With current technologies only limited versions of fully cognitive applications could be realized, in particular when operation frequencies are in the GHz range.

Another interesting application is wireless ad-hoc networks with large number of extremely low-cost, low-power elements. For example, all the required components of a wireless sensor node, i.e., a sensing unit, a processing unit, a transceiver unit, and a power unit have already been demonstrated with nanoelements, such as carbon nanotubes [2]. However, a lot of work remains to make these components suitable for nanosize wireless sensor nodes, and to integrate them together into a complete system. Once realized, this could enable a vast number of novel applications and possibilities of ultra-low power wireless sensor networks that have not been possible before. In addition to communication networks and environmental sensors, also applications to medicine and healthcare can be significant.

Nanotechnology also offers new possibilities for antennas. Reducing the size of current antennas made from magnetic and conducting bulk material increases electromagnetic dissipation. The antenna geometry can be optimized using numerical simulations, but the radical enhancement of the performance could come from nanotechnology: by tailoring new materials, e.g., magnetic nanoparticles, we can hope to reduce the losses and tune the electrical permittivity and permeability to optimal values. Another intriguing possibility is metamaterials, which exhibit physical properties not appearing conventionally in nature [3]. Such materials/structures are attractive for antennas, filters, or near field imaging.

IV. MORE SPEED, LESS ENERGY

Ever increasing wireless communication speeds require increasing amount of computation with limited power. Continued innovation has made it possible to follow the Moore's law and to provide electronics with all the time increasing performance with reduced price. The current approach of simply reducing the transistor size seems to come to an end by about 2015 due to the limitations of the manufacturing technology [4]. By 2020, the traditional silicon CMOS is expected to reach a density of 10^{10} devices per cm^2, switching speed of 12 THz, circuit speed of 61 GHz, and switching energy of $3x10^{-18}$J [4]. This should be considered a benchmark for new approaches based on nanotechnology.

Such approaches include new materials leading to transistors with improved properties (for example Intel's recent announcement on metal gate high-k transistors [5]), and combination of new type of nanoelements with traditional circuits [6]. Some circuitry can be replaced with application specific nanosystems, either digital or analogue, tailored to perform a specific signal processing task with vastly improved power efficiency and speed.

At the nanoscale the operation of the devices is more stochastic in nature and quantum effects become the rule rather than the exception. It could easily be that the current standard computation methods and models will not be optimal with these new devices and technologies. As an example, parallel computing with neural networks could be optimal for processing and understanding information from sensors. Other ideas being studied currently are, e.g., spintronics [7] and cellular automata, realized with spin-based systems of nanosize magnetic particles [8].

System design with these kinds of elements requires development of computing methods which are tolerant to failing components, and capable to take into account quantum-scale effects inherent in nanosystems.

V. MORE MEMORY

Already today mobile phones require a considerable amount of storage capacity to retain pictures, video, music, and data from a number of different applications. Taking into account wider usage of different tools allowing users to create their own content and fast wireless links for loading of external content, we can easily expect that mobile phones will require up to 10 GB internal mass memory for short term and 50-100GB for mid and long terms.

Memories for mobile devices should meet very tough requirements. Low power consumption is required for both active and standby modes. Battery energy is limited (typically 500-1500 mAh) and small factor of products have limited maximum heat dissipation (2-4 W) due to safety and reliability. Low voltage is needed because of power limitations, battery voltage development, and system design. Currently 1.8 V core and I/O is a standard in the mobile industry, and we expect a transition to 1.2 V within 3-5 years.

More functionality is needed in system ASICs, but terminals are not getting any bigger - thus low pin count is an issue. Limited PWB area and package/module height dictates small form factor. Share of memories out of total Bill-Of-Material of the product is significant. So low cost is a key requirement.
So far Flash memory has been the most reliable storage technology for portable devices. However, visible limitations for future Flash cell scaling include power consumption, charge storage requirements of the dielectrics, reliability issues, and capacitive coupling between adjustment cells.
A lot of innovation has been proposed to get over the limitations in Flash, using system management technique and fabrication technology improvements (e.g. high-k dielectrics, nanocrystal storage medias, and Fin-FET).
While there are no doubts that Flash will remain the dominant non-volatile memory technology at least down to 45 nm node, the world is currently taking a hard look at where there might be a better way. Even today semiconductor industry, which produces transistors with critical dimensions well below 100 nm, uses achievements of nanotechnology. However much more can be expected by usage new materials structures at the nanoscale and utilizing new ways to storage information.
A range of new memory technologies have been explored: ferro-electric RAM (FeRAM), magnetic RAM (MRAM), ferro-electric polymer FeRAM, phase change memory (PCM), resistive RAM (RRAM), probe storage, carbon nanotube memory (CNT), molecular memory, and many others. The concept for some of these technologies has been around for years, and even reached product phase like FeRAM, MRAM and PCM. A few are completely new.
All the memory technologies mentioned have different levels of maturity. The status of some of them is shown in Figure 2.
Taking into consideration the requirements for mass storage, the use in portable devices, the size limitations, and the status of the development of the technologies, the most promising choices are probe storage memories and PCM. However, a lot of research and development should be done before they will be able to compete with Flash.

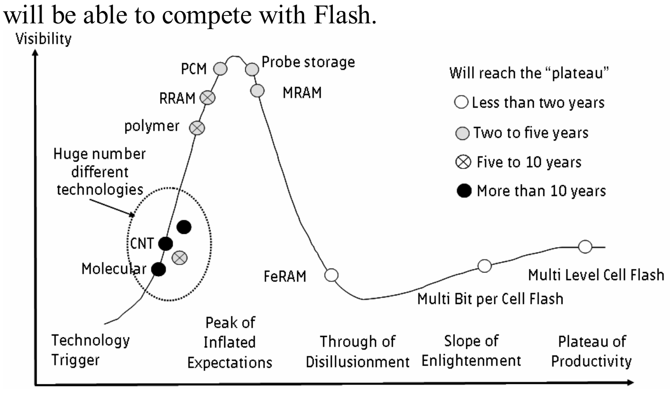

Figure 2: Status of emergency memory technologies

VI. BETTER HUMAN - MACHINE INTERACTION

Form factors and user interface concepts of the mobile multimedia computers will vary according to the usage scenario. The tendency towards smaller and thinner structures as well as towards reliable transformable mechanics will continue. Curved, flexible, compliant, and stretchable structures together with the need for more freedom for industrial design set demanding requirements for the user interface technologies; displays, keyboard, and overall integration of the user interface. A possibility to integrate electronics and user interface functions into structural components, such as covers, will become a necessity.
Furthermore, the concepts of the future intelligent environments require novel means to interact with the smart spaces and to use the mobile personal device as a user interface in this interaction. Interaction paradigms become more intuitive to consumer, but much more complex to implement.
Promise of nanotechnologies for the development of user interfaces and interaction solutions includes intelligent sensors, novel means to create actuation like haptic feedback, and new ways to integrate sensors and actuators into the structural parts of the device.

VII. MORE POSSIBILITIES WITH NEW MATERIALS

Enhanced user experiences created via new, useful device features and functions, good design and usability, and attractive personalized look and feel are major drivers for the development of future communication devices. The wish to have high-performance devices with "all the features" in small, compact physical size and being easy to use and carry, sets high requirements for several technologies. Materials technology is in key role in the development of many areas such as device mechanics, core electronics, advanced user interfaces, displays, energy sources, and data storage, as discussed above.
Currently the device miniaturization is mainly driven by constant miniaturization of the electronic components. As this trend continues, it will also allow designing the device architectures in a new way, more effectively applying novel materials and manufacturing techniques. Rigid thin wall structural parts, effective integration of electronics to device mechanics, and optimized design with multifunctional materials (ref. e.g. thermal management, optimal RF performance) are examples of the current challenges where nanotechnology might bring new solutions (e.g. novel nanocomposites, hybrid materials, printed electronics).
The wish to have transformable devices (easy to carry and use) leads the way from foldable, sliding, and bendable devices towards more wearable electronics. Textiles and fabrics enable flexibility and softness, providing also nice look and feel and a way to customize the products hiding the hard technology. Fibres and fabrics with high strength, wear and chemical resistance, self-cleaning features, electrical conductivity, pressure sensitivity or other sensing properties are examples of existing enablers for wearable devices and advanced user interfaces. A major challenge is however, how to protect the core electronics and achieve good reliability, i.e., "washable electronics". Nanotech research has already resulted in, e.g., super-tough carbon nanotube fibres suitable for weaving [9], and coatings with anti-microbial or super-hydrophobic properties [10], but still much more is expected to be seen in near future.

When looking a bit deeper at the nano science, the future looks attractive. Today's material scientists are playing with biomaterials (proteins, lipids, DNA etc), synthetic block-co-polymers, inorganic (insulating or semiconductive) or metallic nanoparticles (conductive or magnetic), carbon nanomaterials (carbon nanotubes and fibres, fullerene and 2-dimensional graphene), and many others to create novel hybrid materials [11,12,13]. Utilizing self-assembly and molecular recognition, different molecular scale "building blocks" may be combined together to tailor active, smart materials via bottom-up manufacturing. Such active materials, which in some cases can be thought as simple devices, can bring novel functions to electronics devices enabling adaptive, sensing, responsive, or strong but light structures - and boosting the design freedom to a new level. This field, which is still in its infancy, may bring totally new solutions for future communication devices and systems during the next 10-15 years. Deeper understanding on biomaterials, their manipulation and application potential for engineering purposes might also pave the way towards more sustainable material solutions. However, multi-disciplinary research is still needed to exploit the full potential of nanotechnology.

VIII. POWER AND THERMAL MANAGEMENT

Nanotechnologies will contribute to the development energy and power sources mainly because of the very large surface area of nanostructured materials. This is beneficial for the battery technologies, fuel cells, and for different power harvesting devices. Nanotechnologies will also provide new ways to develop hybrid energy solutions. Nanotechnologies may create totally new kind of energy sources for autonomous systems and contribute to the deployment of distributed sensor networks and environmental intelligence.

Miniaturization of future wireless devices and structures has lead to increasing power dissipation densities. This can cause excessive temperatures, if not taken properly into account. Thus, the significance of thermal management as one of the main enabling technologies has recently been emphasised. However, in small scale enough, certain effects can change the situation essentially compared to the traditional approach. For instance, the thermal conductivity of material decreases continuously when approaching nanoscale dimensions due to increasing phonon-boundary scattering. In addition, analysis of the heat transfer gets more difficult when simple macro scale Fourier equation is no more valid. At dimensions comparable to phonon mean free path lengths (~300 nm for Si), much more complicated methods such as the Boltzmann transfer equation must be applied. On the other hand, the advance of nanotechnology may provide novel die level cooling methods, such as greatly improved superlattice thermoelectric coolers. Transfer towards nano scale thus provides us both with new challenges as well as opportunities. [14,15]

IX. SIMULATIONS MAKE THIS POSSIBLE

Numerical modelling remains essential for integration of multi scale functionalities to the future products. While the current mode of working for simulations of predicting and optimizing the performance of a product is to start with a Computer Aided Design (CAD) drawing, and then calculating the physical properties using continuum simulations [16], the products based on nanotechnology require a different approach. The power of nanotechnology is to be able to tailor the material at the atomistic scale in order to have the desired properties at the larger, more macroscopic scale. The simulation techniques have to reflect this bottom-up approach, too. Starting from solving Schrödinger equation for the electrons and ions, then predicting ordering and movement of atoms using estimated interaction forces between the atoms, and finally drawing the continuum behavior from them, give the linking of different length scales. Besides the derivation of the behavior starting from the lowest scale, also concomitant combination of the different length and time scales needs to be included in the simulations.

Thus when using nanotechnology the simulations need to be simultaneously from top down - from CAD drawing to physical quantities - and from bottom up - from electrons to continuum. This requires linking of different scales, which is a difficult question for state-of-the-art basic research.

X. MANUFACTURING AND ENVIRONMENT

Although many promising scientific results have emerged from nanotechnology, the real challenge for many nanotechnology topics is up-scaling from laboratory work to industrial scale manufacturing. On the other hand, novel manufacturing and fabrication methods related to nanotechnology may be key enablers for future electronics manufacturing.

Printed electronics and related reel-to-reel manufacturing may be the first disruptive solutions that enable new kind of electronics industry: low cost, large area electronics that will open new applications in embedding electronics into human environments; we can imagine wall sized, interactive, touch sensitive panels, or new low cost useful computing and communication devices for developing countries. RFID technologies are clearly the first area where the manufacturing solutions based on bottom up self-assembling processes could simplify electronics manufacturing and lower the investments and assets needed for establishing manufacturing sites.

The introduction of new materials and manufacturing solutions always has some risks. During the last five years understanding and knowledge about the risks of nanoscale particles and nanotechnologies have increased substantially. Our approach needs to be careful and responsible.

The responsible introduction of nanotechnologies requires dedicated research of biological risks of nanomaterials, policies for risk management in research, production, and recycling, and objective information sharing with the public arena.

Size of the particles is shown to be the dominant factor determining the rate of biological uptake of particles on the surface of the living cells (for a review on these topics, see [17]). Furthermore, commonly used metal oxide nanoparticles have been demonstrated to show clear cytotoxicity in *in vitro* experiments. Similarly, there exists evidence of *in vitro* toxicity of fullerenes and carbon nanotubes. However, these results do not necessarily mean that a living tissue cannot handle the exposure to strange particles. In fact we are constantly exposed to nanoscale particles in natural and urban environments – there exists a natural background. Exceeding this background substantially should be avoided based on current understanding.

Instead of concentrating only on the potential hazards, we can also think about the use of nanotechnologies in a positive way. We can set the targets and objectives of the research so that they can help us to solve the environmental challenges that we will have in front of us during the coming decades: we should develop new electronics materials that are easier to recycle and/or decomposable in biological processes, and optimize and minimize the energy consumption in the manufacturing of future materials and products.

Let us set the targets right – focus in the right set of technologies and introduce nanotechnologies into the public arena in a responsible way. Nanotechnologies can be one key solution towards sustainable future.

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