

Nanoscale Communication: State-of-Art and Recent Advances

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Abstract

The engineering community is witnessing a new frontier in the communication industry. Among others, the tools provided by nanotechnologies enable the development of novel nanosensors and nanomachines. On the one hand, nanosensors are capable of detecting events with unprecedented accuracy. On the other hand, nanomachines are envisioned to accomplish tasks ranging from computing and data storing to sensing and actuation. Recently, in vivo wireless nanosensor networks (iWNSNs) have been presented to provide fast and accurate disease diagnosis and treatment. These networks are capable of operating inside the human body in real time and will be of great benefit for medical monitoring and medical implant communication. Despite the fact that nanodevice technology has been witnessing great advancements, enabling the communication among nanomachines is still a major challenge.

I. CHAPTER OVERVIEW

The last two decades witnessed an exponential growth and tremendous developments in wireless technologies and systems, and their associated applications, such as those reported in [1]–[41]. In recent decades, the technological advances in novel materials have enabled a new generation of increasingly smaller electronics, which are fundamental tools for the future development of components such as processors, batteries, sensors and actuators. The downsizing of electronics to the scale of a few nanometers opens the analysis of different, unforeseen essential parameters and magnitudes, such as hormone levels, disease detection, control of bio-implants in human or animal bodies as well as air pollution measurements in the atmosphere, among others.

In this chapter, the concept of nanonetworks is going to be discussed along with an extensive explanation of the nanomachine hardware architecture. In addition, a plethora of potential applications in fields such as biomedicine, environmental sciences and industry are going to be addressed. The chapter concludes by presenting current developments of nanoscale devices which aim to provide additional capacities for attaining novel technological solutions.

II. NANONETWORKS

Nanotechnology is providing a new set of tools to the engineering community to create nanoscale components that are able to perform simple tasks, such as computing, data storing, sensing, and actuation. Integrating several of these nanocomponents into a single device just a few cubic micrometers in size will enable the development of more advanced nanodevices and will further allow these devices to achieve complex tasks in a distributed manner [42]. The resulting nanonetworks will permit unique applications in the biomedical, industrial, and military fields, such as advanced health monitoring systems, nanosensor networks for biological and chemical attack prevention as well as wireless network on chip systems for very large multicore computing architecture [43]. Fig 1 illustrates the concept behind nanomachine design in which it could be inspired by following either a top-down or a bottom-up approach, which are two major means commonly utilized in product manufacturing.

Several communication paradigms can be used in nanonetworks depending on the technology deployed to synthesize the nanomachine and the targeted application. In this chapter, the focus will be on nanoelectromagnetic communication which is defined as the transmission and reception of electromagnetic radiation from components based on novel nanomaterials [44]. From a communication perspective, the unique properties observed in novel nanomaterials will decide on the specific bandwidths for emission of electromagnetic radiation, the time lag of the emission or the magnitude of the emitted power for a given input energy [45].

III. NANOMACHINE HARDWARE ARCHITECTURE

There are numerous challenges in the development of autonomous nanomachines. In Fig. 2, a conceptual nanomachine architecture is shown. To the best of our knowledge, fully functional nanomachines have not been built to date. However, several solutions for each nanocomponent have been prototyped and tested as follows.

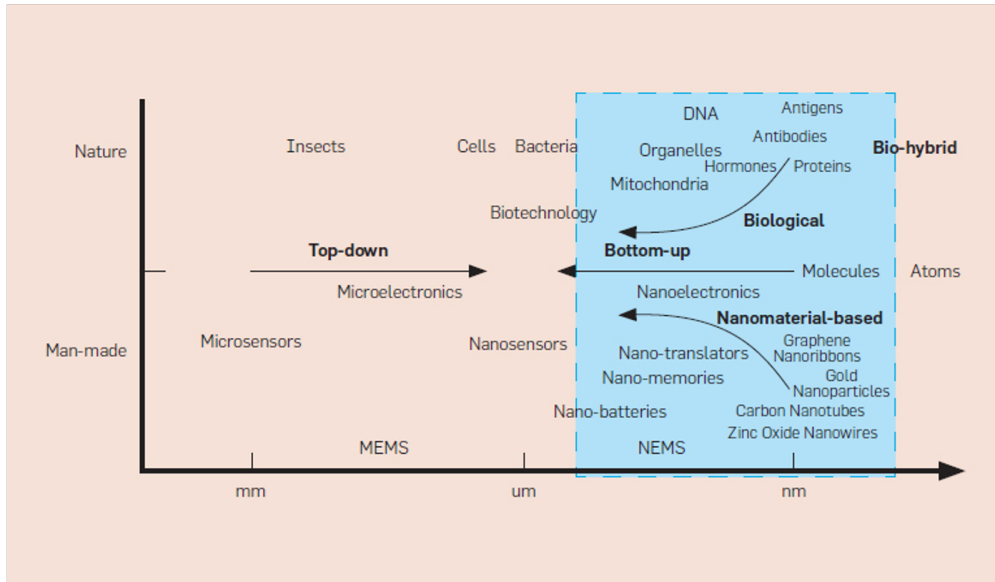


Fig. 1: Illustration of the concept behind nanomachine design [46].

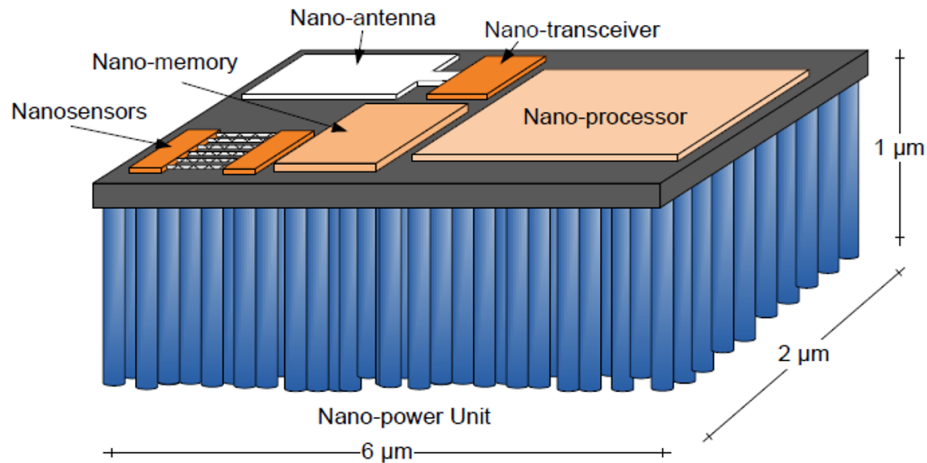


Fig. 2: Nanomachine hardware architecture [46].

- **Processing Unit:** Nanoprocessors are being enabled by the development of tinier Field Effect Transistors (FET) in different forms. The smallest transistor that has been experimentally tested to date is based on a thin graphene strip made of just 10 by 1 carbon atoms [47]. These transistors are not only smaller, but also able to operate at higher frequencies. The complexity of the operations that a nanoprocessor will be able to handle directly depends on the number of integrated transistors in the chip, thus, on total size. Table I reviews the related transistor manufacturing technologies, comparing their scalability, power consumption and

fabrication process.

TABLE I: Comparison of Nanoprocessor Technologies [48]

Transistor Technology	Minimum Transistor Size	Advantages	Disadvantages	Feasibility
Silicon	14 nm	Mature Technology Low-cost manufacturing	Scalability concerns	Yes
Silicon Germanium (SiGe)	7 nm	Good scalability Low-cost manufacturing Ultra-low power consumption	Experimental technology	Yes
Carbon Nanotube (CNT)	Sub 20 nm	Great scalability Ultra-low power consumption High speed	Experimental technology Difficult manufacturing	Yes
Atomic	One atom thick	Ultra-small size	Operation under strict laboratory conditions	Not yet

- **Data Storage Unit:** The storage capacity of an electronic device is an important aspect since the amount and complexity of the stored programming codes rely directly on the available memory. This has an impact on most nanodevice functionalities, as for instance, the communication protocol stack. In this sense, many of its configuration parameters (such as device ID length, packet size, number of bits for error detection, etc.) intrinsically depend on the available memory. Nanomaterials and new manufacturing processes are actually enabling the development of single-atom nanomemories, in which the storage of one bit of information requires only one atom [49]. For example, in a magnetic memory [50], atoms are placed over a surface by means of magnetic forces. While these memories are not ready yet for nanomachines, they serve as a starting point. The total amount of information storable in a nanomemory will ultimately depend on its dimensions.
- **Power Unit:** Powering nanomachines require new types of nanobatteries [51] as well as nanoscale energy harvesting systems [52]. One of the most promising techniques relies on the piezoelectric effect seen in zinc oxide nanowires, which are used to convert vibrational energy into electricity. This energy can then be stored in a nanobattery and dynamically consumed by the device. The rate at which energy is harvested and the total energy that can be stored in a nanodevice depends ultimately on the device size. Recall that as a general

design requirement, our nanodevice size should be similar to the size of a blood cell. This tiny size makes it unfeasible to manipulate it to replace a depleted battery. Thus, to guarantee an appropriate power level to feed the nanodevice efficiently, we consider two solutions: (i) harvesting the energy from the environment (denoted as self-powered nanodevice); and (ii) wireless energy induced from an external power source [53]. Table II compares among existing storing technologies considering their main features.

TABLE II: Comparison Among Storing Technologies [48]

Storage Technology	Advantages	Disadvantages	Feasibility
Batteries	High energy density	High degradation Mechanical properties Use of toxic materials	Not clear
Supercapacitors	High capacitance Ultra low degradation Mechanical properties Non-toxic materials	Low energy density	Yes

- **Sensing Unit:** Physical, chemical and biological nanosensors have been developed by using graphene and other nanomaterials [54]. A nanosensor is not just a tiny sensor, but a device that makes use of the novel properties of nanomaterials to identify and measure new types of events in the nanoscale, such as the physical characteristics of structures just a few nanometers in size, chemical compounds in concentrations as low as one part per billion, or the presence of biological agents such as virus, bacteria or cancerous cells. Their accuracy and timeliness is much higher than those of existing sensors.
- **Communication Unit:** The miniaturization of an antenna to meet the size constraints of nanomachines would impose the use of very high frequencies. This would limit the feasibility of electromagnetic nanonetworks due to the energy limitations of nanomachines. Nanomaterials can be used to develop new types of nanoantennas as well as nanotransceivers, which can operate at much lower frequencies than miniature metallic antennas. However, these introduce many challenges for the realization of communication in nanonetworks.

IV. APPLICATIONS OF NANONETWORKS

The most common application areas of nanonetworks will be biology, medicine, chemistry, environmental science as well as the development of military, industrial and consumer goods [43]. In the area of biomedicine, applications such as health monitoring systems that probe the amount of sodium, glucose and other ions in the blood or drug delivery systems that distribute drugs to special parts of the body with controlled doses are envisioned. Plant monitoring systems as well as plague defeating systems are preliminary environmental applications. As for industrial applications, nanosensors could be used in developing new touch surfaces or haptic interfaces. They could be also used to design equipments required for augmented reality or game applications. The future may reveal some new applications that are now not even envisioned.

A. Biomedical Applications

The most important and immediate applications of nanonodes are in the biomedical area. Nanonodes can interact with organs and tissues. This is clearly provided due to the nanosize, biocompatibility and biostability. Nanomachines deployed inside the human body are remotely controlled from the macroscale and over the Internet by an external user such as a healthcare provider as illustrated in Fig. 3.

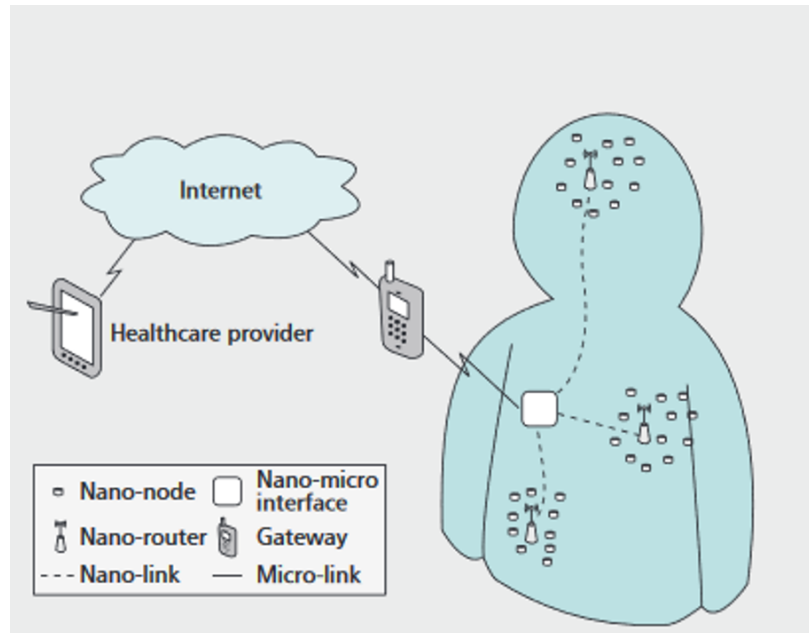


Fig. 3: Intrabody nanonetworks for healthcare applications [55].

Moreover, an immune system can be composed of several nanomachines that protect an organism against diseases. These nanomachines can act in a coordinated way to identify, control, and eliminate foreign and pathogen elements. They could realize tasks of localization and respond to malicious agents and cells, such as cancer cells [56], resulting in less aggressive and invasive treatments compared to the existing ones.

The monitoring of oxygen and cholesterol levels, hormonal disorders, and early diagnosis are some examples of possible applications that can take advantage of intrabody nanosensor networks. The information retrieved by these systems must be accessible outside the body to doctors, nurses, etc. Thus, nanonetworks must provide the proper level of connectivity to deliver the sensed information. In addition, a drug delivery system that is composed of nanonodes could help compensate metabolic diseases such as diabetes. In this scenario, nanosensors and smart glucose reservoirs can work in a cooperative manner to support regulating mechanisms. One other promising application of the nanosensors is checking for bacteria or viruses in hospitals [57]. If contaminating bacteria can be located, it is possible to reduce the number of patients who develop complications such as contagious infections. Finally, manipulation and modification of nanostructures such as molecular sequences and genes can be achieved by nanomachines. The use of nanonetworks will actually allow expanding the potential applications in genetic engineering.

B. Environmental Applications

Trees, herbs or bushes, release several chemical compositions to the air in order to attract the natural predators of the insects that are attacking them, or to regulate their blooming among different plantations, amongst others [58] [59]. Chemical nanosensors [60] could be used to detect the chemical compounds that are being released and exchanged between plants. Nanonetworks can be build around classical sensor devices which are already deployed in agricultural fields [61]. Other environmental applications include biodiversity control, biodegradation assistance, or air pollution control [62].

C. Industrial Applications

The applications of nanotechnology in the development of new industrial and consumer goods range from flexible and stretchable electronic devices [63] to new functionalized nanomaterials for self cleaning anti-microbial textiles [64]. In addition, the integration of nanomachines with

communication capabilities in every single object will allow the interaction of almost everything in our daily life, from cooking utensils to every element in our working place, or also the components of every device, enabling what we define as the Internet of Nano Things (IoNT) [55]. Moreover, as nanocameras and nanophones are developed, in a more futuristic approach, the Internet of Multimedia Nano Things will also become a reality [65]. Fig. 4 presents a schematic of a future interconnected office envisaging the concept of nanonetworks where the users can keep track of the location and status of all their belongings in an effortless fashion.

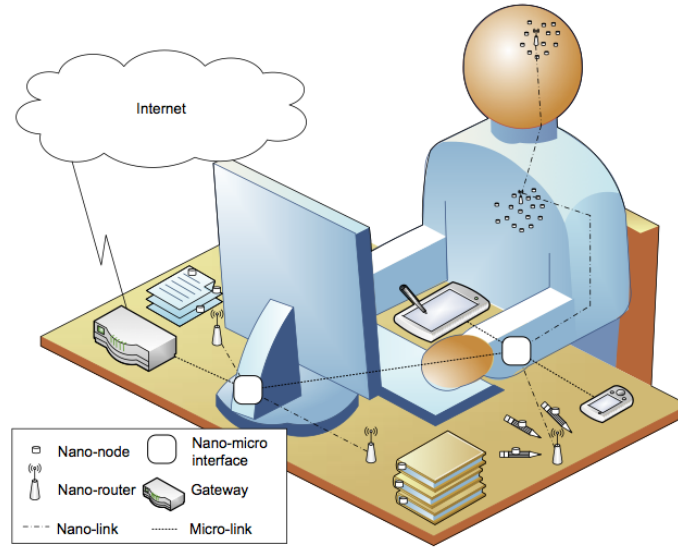


Fig. 4: Schematic of an intelligent office [55].

V. CURRENT DEVELOPMENTS OF NANOSCALE DEVICES

Due to the developments in micro-fabrication and nanotechnologies, the limits of the sizes and capabilities of devices have been pushed further. The initial goal of developing small-scale devices is to replace the existing tethered medical devices such as flexible endoscopes and catheters with devices capable of accessing complex and small regions of the human body like the gastrointestinal tract, spinal cord, and blood capillaries. At the same time, the patient discomfort as well as tissue loss due to sedation would be hugely decreased. Fig. 5 demonstrates a chip that is smaller than a grain of rice designed by the National Applied Research Laboratory, using sensor fusion technologies. The micro-robots voyaging around human body were developed recently according to the same principles as well. For example, a tiny permanent magnet, guided inside the human body by a magnetic stereotaxis system was proposed in [66] while a magnetically

driven screw was made to move through tissues as presented in [67]. Micro-mechanical flying insect robots were first created in the University of California, Berkeley [68] and then later a solar-powered crawling robot was realized in [69]. The first medical-used capsule endoscopes were applied clinically in 2001 after attaining the Food and Drug Administration (FDA) approval. Later, the introduction of a crawling mechanism [70] and on-board drug delivery mechanism [71] were marked as milestones for the development of capsule endoscopy. A nano-scallop, presented in Fig. 6, whose size is only a fraction of millimetre and is capable of swimming in biomedical fluids, has been developed at the Max Planck Institute for Intelligent Systems [72].

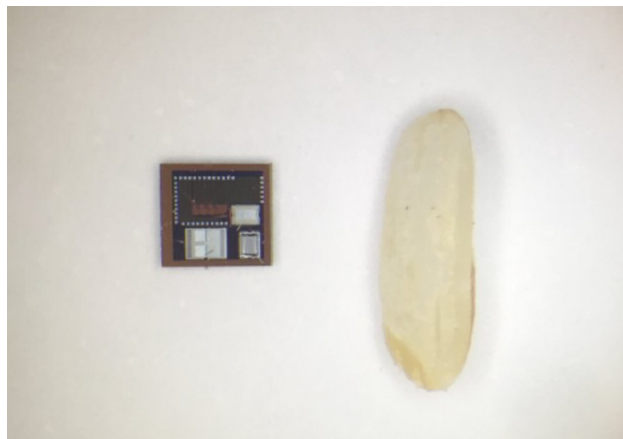


Fig. 5: Integrated Chip developed by National Applied Research Laboratory with a size comparable to a grain of rice [73].



Fig. 6: Nano-scallop which can swim in bio-fluids [72].

On another hand, a surgical nanorobot, programmed or guided by a human surgeon could act as a semi-autonomous on site surgeon when introduced into the body through vascular system

or body cavities [74]. These devices could perform various functions such as diagnosing and correcting lesions by nano-manipulation. Such mechanism is coordinated by an onboard computer while maintaining contact with the supervising surgeon via coded ultrasound signals. Basically, programmable and controllable microscale robots comprised of nanoscale parts fabricated to nanometer precision will allow medical doctors to execute creative and reconstructive procedures in the human body at the cellular and molecular levels [75].

Besides the research activities on tiny robots, there are also investigations on other applications. A wireless radiation detector was designed to be injected into tumors to detect the level of therapeutic radiation the tumor gets [76]. Applying micro-machining techniques, this dosimeter was shrunk to 2 cm long and 2 mm wide in diameter. Overall, reduction in sensor size provides great versatility for incorporation into multiplexed, portable, wearable, as well as implantable medical devices [77]. The integration of nanoscale ultrasensitive biosensors with other medical instruments will open the door to emerging medical fields, including point-of-care diagnostics and ubiquitous healthcare systems [78]. Specifically, the future impact of nanobiosensor systems for point-of-care diagnostics will be unmatched. This technology will revolutionize conventional medical practices by enabling early diagnosis of chronic debilitating diseases, ultrasensitive detection of pathogens, and long-term monitoring of patients using biocompatible integrated medical instrumentation [79].

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