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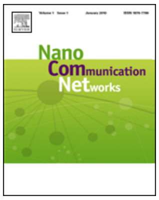

Electromagnetic wireless nanosensor networks

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ABSTRACT

This paper provides an in-depth view on nanosensor technology and electromagnetic communication among nanosensors. First, the state of the art in nanosensor technology is surveyed from the device perspective, by explaining the details of the architecture and components of individual nanosensors, as well as the existing manufacturing and integration techniques for nanosensor devices. Some interesting applications of wireless nanosensor networks are highlighted to emphasize the need for communication among nanosensor devices. A new network architecture for the interconnection of nanosensor devices with existing communication networks is provided. The communication challenges in terms of terahertz channel modeling, information encoding and protocols for nanosensor networks are highlighted, defining a roadmap for the development of this new networking paradigm.

1. Introduction

Nanotechnology is enabling the development of devices in a scale ranging from one to a few hundred nanometers. At this scale, novel nanomaterials and nanoparticles show new properties and behaviors not observed at the microscopic level. The aim of nanotechnology is on creating nano-devices with new functionalities stemming from these unique characteristics, not on just developing miniaturized classical machines.

One of the early applications of nanotechnology is in the field of nanosensors [100,68,31,51]. A nanosensor is not necessarily a device merely reduced in size to a few nanometers, but a device that makes use of the unique properties of nanomaterials and nanoparticles to detect and measure new types of events in the nanoscale. For example, nanosensors can detect chemical compounds in concentrations as low as one part per billion [75,70], or the presence of different infectious agents such as virus or harmful bacteria [99,82].

Communication among nanosensors will expand the capabilities and applications of individual nano-devices both in terms of complexity and range of operation. The detection range of existing nanosensors requires them to be inside the phenomenon that is being measured, and the area covered by a single nanosensor is limited to its close environment. A network of nanosensors will be able to cover larger areas and perform additional in-network processing. In addition, several existing nanoscale sensing technologies require the use of external excitation and measurement equipment to operate. Wireless communication between nanosensors and micro- and macro-devices will eliminate this need.

For the time being, it is still not clear how these nanosensor devices will communicate. We envision two main alternatives for communication in the nanoscale, namely, molecular communication and nano-electromagnetic communication (Fig. 1):

- *Molecular communication:* this is defined as the transmission and reception of information encoded in molecules [1,81,58]. Molecular transceivers will be easy to integrate in nano-devices due to their size and domain of operation. These transceivers are able to react to specific molecules and to release others as a response to an internal command or after performing some type of processing. The released molecules are propagated either following spontaneous diffusion in a fluidic medium (diffusion-based); through diffusion in

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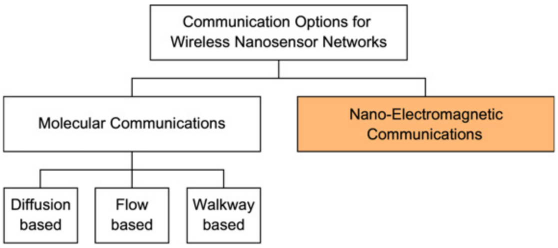


Fig. 1. Communication options for wireless nanosensor networks.

a fluidic medium whose flow is guided (flow-based); or through active carriers that transport them through pre-defined pathways (walkway-based). This radically different communication paradigm necessitates novel channel models [61], network architectures [24] and communication protocols.

- *Nano-electromagnetic communication:* this is defined as the transmission and reception of electromagnetic radiation from components based on novel nanomaterials [73]. Recent advancements in molecular and carbon electronics have opened the door to a new generation of electronic nano-components such as nanobatteries, nano-memories, logical circuitry in the nanoscale and even nano-antennas [10]. From a communication perspective, the unique properties observed in novel nanomaterials will decide on the specific bandwidths for emission of electromagnetic radiation [39], the time lag of the emission, or the magnitude of the emitted power for a given input energy. All these entail a fundamental change in the current state of the art of analytical channel models [40], network architectures and communication protocols [3].

In [1], an extensive study on molecular communications and nanonetworks is provided. In this paper, we focus on nano-electromagnetic communications for Wireless Nanosensor Networks (WNSNs). Our aim is to provide a better understanding of the current research issues in this truly interdisciplinary and emerging field led by nanotechnology, and to pave the way for future electromagnetic nanosensor networks.

The remaining of this paper is organized as follows. In Section 2, the state of the art in nanosensor technology is reviewed, providing details on the hardware architecture and the main components that integrate a nanosensor device. The manufacturing and integration techniques of nanosensor devices are described in Section 3. An overview of the main applications of nanosensors is given in Section 4, by highlighting the communication needs of nanosensor devices. A new network architecture for the interconnection of nanosensor devices with existing communication networks and ultimately Internet is provided in Section 5. In Section 6, the open research challenges in terms of terahertz channel modeling, network architectures and protocols for nanosensor networks are covered in detail. Finally, the paper is concluded in Section 7.

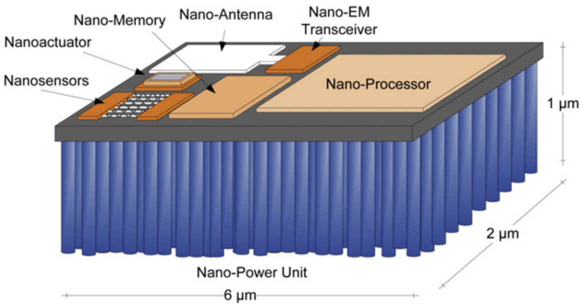


Fig. 2. An integrated nanosensor device.

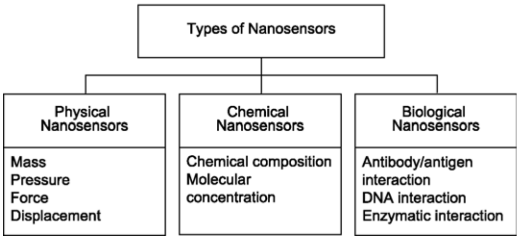


Fig. 3. Types of nanosensors.

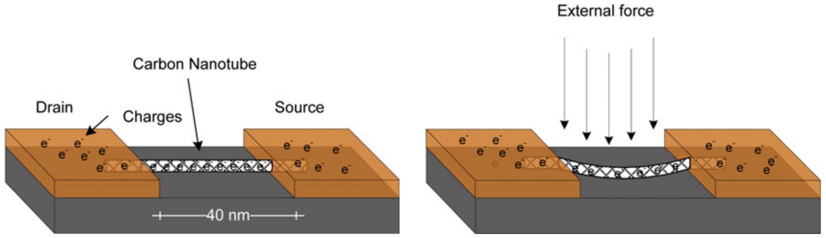
2. Nanosensor device architecture

We think of a nanosensor as an integrated device around 10–100 μm^2 in size able to do simple tasks besides sensing, such as simple computation or even local actuation. The internal abstract architecture of a nanosensor device is shown in Fig. 2. Despite being similar to micro- and macroscale sensors [2], it should be taken into account that (i) the solutions in the nanoscale are limited not just in terms of existing manufacturing technologies but also by the physics laws, i.e., we cannot think of a nanosensor as a small and simplified sensor, and (ii) there will be a strong compromise between the size of the nanosensor, its capabilities, and the type of applications in which it can be used. In the following, we present different potential solutions for the implementation of each sub-block composing a nanosensor.

2.1. Sensing unit

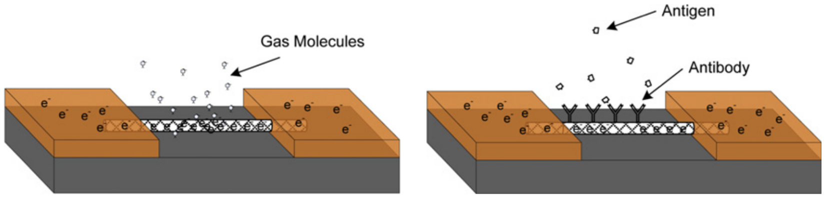
Novel nanomaterials such as graphene and its derivatives, namely, Graphene Nanoribbons (GNRs) and Carbon Nanotubes (CNTs) [4], provide outstanding sensing capabilities and are the basis for many types of sensors [100]. Based on the nature of the measured magnitude, nanosensors can be classified as follows (Fig. 3):

- *Physical nanosensors*: these are used to measure magnitudes such as mass, pressure, force, or displacement. Their working principle is usually based on the fact that the electronic properties of both nanotubes and nanoribbons change when these are bent or deformed [31]. For example, a CNT can be used to build a field-effect transistor (FET) nano in size, whose on/off threshold depends on the tube dimensions, shape and temperature, amongst others. A local deformation of the tube creates a change in the on/off threshold voltage of the transistor. Starting from this simple principle, different types of nano-electromechanical



(a) CNT-based FET transistor.

(b) Physical nanosensor.



(c) Chemical nanosensor.

(d) Biological nanosensor.

Fig. 4. Illustration of the working principle of CNT-based physical, chemical and biological nanosensors.

systems (NEMSs) have been proposed in the literature with different applications, such as pressure nanosensors [77], force nanosensors [78] or displacement nanosensors [79].

- *Chemical nanosensors*: these are used to measure magnitudes such as the concentration of a given gas, the presence of a specific type of molecules, or the molecular composition of a substance. The functioning of the most common type of chemical nanosensors is based on the fact that the electronic properties of CNTs and GNRs change when different types of molecules are adsorbed on top of them, which locally increase or decrease the number of electrons able to move through the carbon lattice [8]. Similarly to physical sensors, when a nanotube or a nanoribbon is used in a transistor configuration, the presence of a specific type of molecules changes the on/off threshold voltage of the transistor [70,48]. For the time being, hundreds of chemical nanosensors based on this simple principle have been manufactured with different specific detection targets [8].
- *Biological nanosensors*: these are used to monitor biomolecular processes such as antibody/antigen interactions, DNA interactions, enzymatic interactions or cellular communication processes, amongst others. A biological nanosensor is usually composed of (i) a biological recognition system or *bioreceptor*, such as an antibody, an enzyme, a protein or a DNA strain, and (ii) a transduction mechanism, e.g., an electrochemical detector, an optical transducer, or an amperometric, voltaic or magnetic detector [87]. There are mainly two subtypes of biological nanosensors based on their working principle: electrochemical biological nanosensors and photometric biological nanosensors. The *electrochemical biological sensors* work in a similar way to chemical nanosensors, but in this case, the change in the electronic properties of, for example, a CNT-based FET transistor, is induced either by:
    (i) A protein or any other chemical composite that binds itself to the functionalized nanotube [53].
    (ii) A specific antigen that binds itself to an antibody glued to the nanotube [43].
    (iii) A single stranded DNA chain that binds itself to another DNA chain which has been attached to the nanotube [14].

  Based on this principle, nanosensors able to detect lung cancer, asthma attacks, different common virus such as the *influenza* virus, or the parasite responsible for *malaria*, have been already successfully manufactured [99,82].

  The second subtype of biological nanosensors is based on the use of noble metal nanoparticles and the excitation using optical waves of surface plasmons, i.e., coherent electron waves at the interfaces between these particles. Simply stated, the resonant frequency of the surface plasmons resulting from light irradiation changes when different materials are adsorbed on and in between the particles. This technique, known as localized surface plasmon resonance (LPSR), is the underlying principle behind many biological nanosensors [50,96]. One of the main constraints of this sensing mechanism is the requirement of an external source of light and a device which is able to measure and compare different resonant frequencies of the particles. We believe that this can be overcome by means of coordination and communication among nanosensors. For example, nanosensors could locally irradiate the same particles with a much lower power and measure the reradiated energy at different frequencies. The result of this operation could then be processed or forwarded to a data sink.

In Fig. 4, we illustrate the basic working principle of the three main types of nanosensors. In Fig. 4(a), an unperturbed field-effect transistor based on a carbon nanotube is given. A CNT-based FET is mainly composed of a nanotube suspended over two electrodes. Assuming that the CNT has the adequate geometry to behave as a semiconducting material [16], electrons from the source will be able to reach the drain only if an energy above the conducting threshold is applied on the nanotube. This threshold can be altered either when the tube is bent, Fig. 4(b); when the amount of free charges on the tube is increased or decreased by the presence of donor or acceptor molecules of specific gases or composites, Fig. 4(c); or when the tube has been functionalized with a biological receptor such as an antibody and this is bound to the specific antigen of a given disease, locally changing the number of electric charge in the tube, Fig. 4(d).

There exist several research challenges for nanosensor design. First, the recovery time of chemical and biological nanosensors needs to be reduced. The majority of the nanosensors is reusable, i.e, once the phenomenon that was measured has disappeared, nanosensors return to their initial state after some time which is commonly referred as the recovery time. Currently, the sensing time of a chemical or biological nanosensor is below one minute, whereas the time that they need to return to their initial state is in the order of tens of minutes [60], too long for specific applications such as chemical attack prevention. Second, the selectivity of chemical nanosensors needs to be increased. Different types of molecules will cause the same output from the sensing unit. This is solved for biological nanosensors by using nanotubes, nanoribbons and nanoparticles functionalized with biological entities that will only interact with their specific counterparts. For example, in a biological nanosensor a specific antibody will only react against a specific antigen. Last but not least, it would be interesting to standardize the magnitude and value range of the output of the nanosensor unit in order to make them interchangeable among different nano-device platforms.

2.2. Actuation unit

An actuation unit will allow nanosensors to interact with their close environment. Several nanoactuators have also been designed and implemented so far [51]. They can be classified as:

- *Physical nanoactuators*: these are typically based on NEMS. In the same way that a physical deformation of a nanotube creates a change in the electrical properties of the nanomaterial, an electrical current or an electromagnetic wave can bend a nanotube [51]. Starting from this principle, in [46], a nanotweezer composed of two multi-walled carbon nanotubes is proposed. The nanotweezer was closed by applying a specific voltage and opened by means of external macroactuators. Based on this, we can think of nanoscissors, nanopumps and other utensils that could be useful for example in medical applications. These nanoactuation units will be mounted in the nanosensor device.
- *Chemical and biological nanoactuators*: these are mainly based on the interaction between nanomaterials and nanoparticles, electromagnetic fields and heat. For example, nanoheaters based on magnetic nanoparticles can be used to selectively damage or kill cancer cells by heating them [38,21]. Magnetic nanoparticles and gold nanoshells can also be used for targeted drug delivery, in which the drug containers are melted by applying local heat [22]. By functionalizing the nanoparticles with biological agents such as antibodies or single stranded DNA chains, we can force these particles to bind preferably to specific target cells. For the time being, these nanoparticles are irradiated using external light sources. By using nanosensors and nanoactuators, they could be locally irradiated, requiring much less power and enabling less invasive treatments.

The area of nanoactuators is at a very early stage when compared to nanosensors. The main research challenge, besides the design and fabrication of the actuation unit, is on how to precisely control and drive the nanoactuator. The majority of potential applications of these nanosensors will be in the biomedical field, therefore, the accuracy is one of the fundamental requirements for nanoactuators.

2.3. Power unit

To date, a major effort has been undertaken to reduce existing power sources to the microscale and the nanoscale. Nanomaterials can be used to manufacture nanobatteries with high power density, reasonable lifetime and contained charge/discharge rates. For example, in [88,89] lithium nanobatteries were constructed using alumina membranes having pores 200 nm in diameter. Each one of these pores was filled with PEO–lithium triflate electrolyte and capped with a cathode material, becoming an effective nanobattery. The measured volumetric capacity for each individual nanobattery was in the order of 45 $\mu\text{Ah}^{-1}\ \text{cm}^{-2}\mu\text{m}^{-1}$, proving their potential for powering nano-devices. However, having to periodically recharge them limits the usefulness of nanobatteries in realistic nanosensors' applications.

In order to overcome the limitations of nanobatteries, the concept of self-powered nano-devices has been recently introduced in [90,97]. The working principle of these devices is based on the conversion of the following types of energy into electrical energy:

- *Mechanical energy*: produced for example by the human body movements, or muscle stretching.
- *Vibrational energy*: generated by acoustic waves or structural vibrations of buildings, amongst others.
- *Hydraulic energy*: produced by body fluids, or the blood flow.

This conversion is obtained by means of the piezoelectric effect seen in zinc oxide (ZnO) nanowires. Simply stated, when these nanowires are subject to mechanical deformation, such as when they are bent, a voltage appears in the nanowires (Fig. 5). In addition, nanotubes and nanocantilevers can be designed to absorb vibrational energy at specific frequencies [76]. Moreover, it has been recently demonstrated that a nonlinear oscillator can be used to harvest energy from wide spectrum vibrations or even mechanical and thermal noise [12]. The resulting energy can be directly used by the device or used to charge a nanobattery [80].

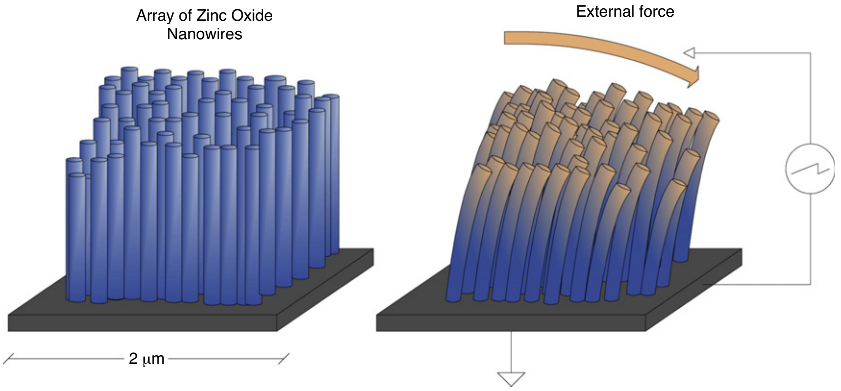


Fig. 5. Nanoscale energy-harvesting system based on the piezoelectric effect of zinc oxide (ZnO) nanowires.

Our vision is that harvesting energy from the environment is the most useful solution for powering nanosensors. In addition to mechanical, vibrational or hydraulic energy, we believe that it will be possible to harvest energy from electromagnetic waves in the nanoscale. For example, a resonator based on a NEMS can be used to convert EM radiation into vibrational energy, and this can be converted into electricity by means of ZnO nanowires. Alternatively, nanoscale *rectennas* [25], i.e., rectifying antennas that convert electromagnetic waves into DC electricity, could be developed using CNTs. In addition, the use of CNTs to develop solar nano-cells is also suggested in [41]. Another option would be to develop synthetic chemical batteries based on ATP or *adenosine triphosphate*, the energy source of cells and living organisms [55], which could be harvested from the medium or even obtained by chemical reactions in the nanoscale emulating cell respiration. Independently of the solution adopted, there will be a strong compromise between the power unit size, the total energy harvested and stored, and the capabilities of an integrated nanosensor device, and this should be taken into account in almost every detail of WNSNs design.

2.4. Processing unit

Nanoscale processors are being enabled by the development of tinier FET transistors in different forms. Nanomaterials, such as CNTs and specially GNRs, can be used to build transistors in the nanometer scale. For instance, the smallest transistor that has been experimentally developed up to date [67] is based on a thin graphene nanoribbon, made of just 10 by 1 carbon atoms, i.e., less than 1 nm in all its dimensions.

Graphene-based transistors are not only smaller, but predictably faster. Graphene shows almost ballistic transport of electrons. As a result, electrons can travel larger distances without being back-scattered and this allows for the development of faster switching devices. In addition, the reduction of the channel length also contributes to a faster response of the transistor. The theoretical predictions for the switching frequencies of graphene-based transistors are in the order of up to a few hundreds of terahertz [56], which is faster than any existing silicon FET transistor for the time being. The small size of nanosensor devices will limit the number of transistors in nanoscale processors, limiting the complexity of the operations that these will be able to do, but not the speed at which nano-processors will be able to operate.

As an alternative to graphene, in [83], a transistor is developed whose active channel is composed of a single phosphorous atom in silicon. In this case, electrons were able to tunnel through the phosphorous atom or not depending on the voltage applied to a nearby metal electrode with a width of just a few tens of nanometers. While the concept of single atom transistors is apparently proved, it is still too early to think of the specific capabilities that a processor based on this technology and limited in size can achieve.

Independently of the specific approach followed to design these nano-transistors, the main challenge is in integrating them in future processor architectures. Experimental testing of individual transistors has been successfully conducted, however, simple processing architectures based on these are still being investigated and, so far, the future processor architectures based on CNTs and graphene still need to be defined.

2.5. Storage unit

Nano-memories utilizing a single atom to store a single bit are being enabled by nanomaterials and new manufacturing processes. Back in 1959, Richard Feynman introduced the concept of atomic memory, i.e., the possibility to store a bit of information in every single atom of a material. In the example he used, Feynman suggested a basic memory unit composed of 5 by 5 by 5 atoms, i.e., 125 atoms in total. He proposed this structure instead of using a single atom in order to prevent potential interference between adjacently stored bits. The resulting 125 atoms for a bit are comparable to the 32 atoms that store one bit of information in DNA [7]. In terms of density, if this were realized with a carbon structure, in which the separation between two atoms is in the order of 0.142 nm [4], the equivalent storage density would be more than 1 bit/nm^3 or 1 gigabit/μm^3.

While this is still a limit to reach, for the time being several types of atomic memories have been proposed. In [7], a memory that stores a bit by the presence or

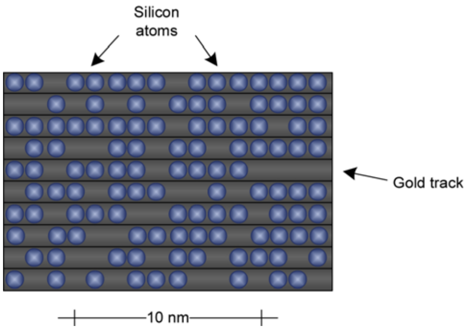


Fig. 6. Atomic memory using single silicon atoms on gold tracks to store digital information.

absence of one silicon atom was developed. Similarly to the tracks in a CD-ROM, the proposed memory was based on a silicon surface with deposited monolayers of gold defining the tracks (Fig. 6). The writing process was performed by means of removing silicon atoms from the gold lattice. Reading the memory was performed by means of a nano-tip able to detect the presence or the absence of silicon atoms. This type of memory is not rewritable, but ways to restore the gold tracks and reset the memory can be envisioned.

More recently, IBM Corp. has demonstrated the concept of magnetic atomic memories [59]. In a magnetic memory, single magnetic atoms are placed over a surface by means of magnetic forces [84]. Each atom can be used to store a bit, as it was shown in [32]. Similarly to gold-based memories, the density that can be achieved with this technology is several orders of magnitude higher than what can be obtained through classical mechanisms. While this technology is still behind the type of memories required in programmable nanosensor devices, it is a major step towards the realization of this paradigm.

Several research challenges for nano-memories are summarized in what follows. First, for the time being, existing nanoscale memories require complex and expensive machinery to be written. Being able to read and write these memories in the nanoscale will be necessary for programmable nanosensor devices. Second, similarly to nano-processors, one of the main challenges is to mass manufacture compact nano-memories beyond simplified laboratory prototypes.

2.6. Communication unit

Electromagnetic communication among nanosensors will be enabled by the development of nano-antennas and the corresponding electromagnetic transceiver. In the following, we describe the latest implementations for these two elements as well as an alternative based on a mechanical resonator.

2.6.1. Nano-antennas

Reducing the antenna of a classical sensor device down to a few hundreds of nanometers would require the use of extremely high operating frequencies, compromising the feasibility of electromagnetic wireless communication among nanosensor devices. However, the usage of graphene to fabricate nano-antennas can overcome this limitation. Indeed, the wave propagation velocity in CNTs and GNRs can be up to one hundred times below the speed of light in vacuum depending on the structure geometry, temperature and Fermi energy [15]. As a result, the resonant frequency of nano-antennas based on graphene can be up to two orders of magnitude below that of nano-antennas built with non-carbon materials.

A few initial antenna designs based on graphene have been already proposed. In [9], the mathematical framework for the analysis of CNTs as potential dipole antennas was developed. In [26], more emphasis was given to the numerical performance analysis of these antennas when compared to classical dipoles. When it comes to GNRs, the propagation of EM waves on a graphene sheet was first analyzed in [27,28]. In [39], nano-patch antennas based on GNRs and nano-dipole antennas based on CNTs are quantitatively compared, illustrating that a graphene nano-antenna 1 μm long can efficiently radiate EM waves in the terahertz band (0.1–10.0 THz). While being the first time that the terahertz radiation properties are pointed out for nanoribbons, the interaction between terahertz waves and carbon nanotubes in reception was previously addressed in [102].

From the optical perspective, the emission of photons from nano-structures due to electron–phonon interaction [5], i.e., the interaction between electrons and vibrating ions in the material, has motivated the study of CNTs and GNRs as optical emitters and detectors. In [71], it is mathematically demonstrated that a quasi-metallic carbon nanotube can emit terahertz radiation when a time varying voltage is applied to its ends. Similarly in [101], the absorption of infrared radiation in a nanotube is experimentally demonstrated. In addition, several ongoing projects are conducting research on optical nano-antennas. An optical nano-antenna is a device which is able to emit energy to the free-space from a confined region with a size in the order of the wavelength of the light [42]. The discovery of nanotubes enabled the development of resonant structures with a size in the order of the light wavelength and triggered the development of this new field [44].

We summarize the research challenges for nano-antennas as follows. First, more accurate models for nano-antennas based on nanotubes and nanoribbons need to be defined by providing details on their specific band of operation, radiation bandwidth and radiation efficiency, amongst others. All these will determine the communication capabilities of nanosensor devices. Second, new nano-antenna designs and radiating nano-structures need to be developed by exploiting the properties of nanomaterials and new manufacturing techniques. Our vision is that it will be possible to create new atomically precise nano-antennas by using graphene, and in which symmetry will play an important role. For example, we can think of fractal nano-antennas able to efficiently resonate at different frequencies within the terahertz band. Last but not least, a new antenna theory must be defined by accounting for the quantum effects observed in the nanoscale.

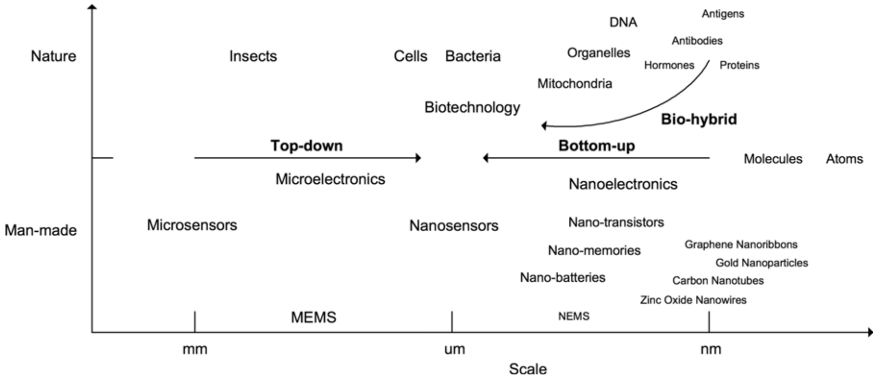


Fig. 7. Approaches for the fabrication and integration of nanosensors.

2.6.2. *EM nano-transceivers*

The EM transceiver of a nanosensor device will embed the necessary circuitry to perform baseband processing, frequency conversion, filtering and power amplification, of the signals that have to be transmitted or that have been received from the free-space through the nano-antenna. Taking into account that the envisioned nano-antennas will resonate at frequencies in the terahertz band, RF FET transistors able to operate at these very high frequencies are necessary.

Several graphene-based FET transistors operating in the sub-terahertz and lower part of the terahertz band have been demonstrated so far. IBM Corp. has recently announced the first RF transistor made with graphene which is able to switch at 100 GHz [52]. Their next target is to make a RF transistor operating at 1 THz. In [54], the RF performance of epitaxial graphene FET transistors was measured, showing the potential of graphene transistors for RF applications. In [92], graphene-based frequency multipliers are implemented with graphene. Fast switching NEMS for RF applications are discussed in [17] by showing that graphene can be used to fabricate oscillators beyond 1 THz.

Several research challenges for graphene-based transceivers are summarized in the following. First, it is necessary to characterize and model electronic noise in graphene-based electronics. The electronic noise has a strong impact on the signal to noise ratio at the receiver and, thus, limits the communication range of nano-devices. Graphene shows almost ballistic transport of electrons for large lengths [20]. As a result, the thermal noise created by inelastic scattering of electrons in the material is very low [57]. More accurate models of noise are necessary. Second, new communication and information modulation techniques need to be developed. Our vision is that the EM transceivers of nanosensor devices will be limited in terms of complexity due to space constraints and integration limits, but not limited in terms of switching speed or electronic noise. For this, we think that it is necessary to simplify existing communication techniques and to develop new ways to exploit these two characteristics.

2.6.3. *Alternatives for the communication unit: an electromechanical resonator*

It has been recently shown that it is possible to receive and demodulate an electromagnetic wave by using a single CNT that mechanically resonates at the wave frequency [72,36]. When a carbon nanotube which has one of its ends connected to a power source and the other end left floating, is irradiated by an EM wave, electrons at the free tip will vibrate. If the frequency of the EM wave matches the natural resonant frequency of the CNT, these vibrations become significant and the nanotube is able to demodulate the incoming signal. For example, a 1 μm long nanotube will mechanically resonate at frequencies around a few hundreds of megahertz. This type of nanoreceiver can only demodulate amplitude modulated or frequency modulated waves. In [94], a mechanical way to generate EM waves is proposed by using the same concept.

We summarize the main research challenges for electromechanical nanoscale communications as follows. First, more accurate models for the electromechanical nanotransceiver are required by accounting for the radiation bandwidth and energy efficiency of the entire process. In particular, it is necessary to evaluate the feasibility of generating EM waves with a mechanical resonator in the nanoscale. Indeed, while a mechanical resonator can receive EM waves with large energies generated in the micro- and macroscale, the EM wave generated by a power limited nano-device may not be enough to make a nanotube resonate. Moreover, even in reception, the nanotube radio requires a very high DC voltage in order to create the necessary conditions for resonance and modulation/demodulation. For the time being, nanobatteries cannot provide these voltages. Second, the noise in reception needs to be characterized by identifying which types of noise affect the electromechanical unit and how these impact on the demodulated signal. Last but not least, new nano-receiver architectures able to support more advanced, robust or bandwidth efficient modulations should be developed. For example, CNTs with different lengths resonating at different frequencies may be simultaneously used [3]. In that case, it will be necessary to characterize the coupling effects between the nanotubes and how they affect the system performance.

3. Nanosensor components manufacturing and integration

There are different techniques to manufacture and integrate the components of nanosensor devices. These can be grouped in three main categories, namely, top-down, bottom-up and bio-hybrid [1] (Fig. 7):

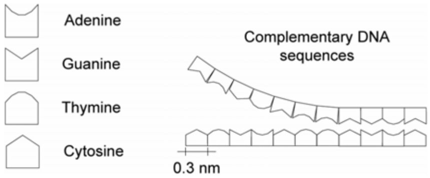


Fig. 8. DNA nucleotides and two complementary sequences being *glued*.

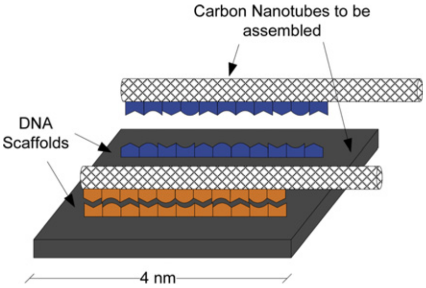


Fig. 9. Two carbon nanotubes precisely connected over a silicon substrate by means of DNA scaffolding.

- In a *top-down* approach, the nano-components are obtained using larger, externally controlled tools from the microscale. Microcontact printing [47], imprint lithography [11] or direct-write dip-pen nanolithography [74] are different nanofabrication techniques currently being used to fabricate components with at least one of their dimensions in a scale below 100 nm [91]. Despite several technological and physical limitations, the evolution of classical lithography techniques and other non-standard procedures have been used to obtain nanoscale components with atomic precision. For example, with an integrated Transmission Electron Microscope–Scanning Tunneling Microscope (TEM–STM) system, atomically precise graphene nanoribbons have been obtained from bulk graphene [37]. These nanoribbons can then be used to build FET transistors, graphene-based sensors or nano-antennas, for example.
- In a *bottom-up* approach, the focus is on having smaller components built up into more complex assemblies. Molecular manufacturing [18], i.e., the process of assembling nano-devices molecule by molecule, exemplifies a bottom-up approach. For the time being, self-assembly of nano-components by DNA scaffolding is one of the most promising techniques. IBM Corp. has recently demonstrated a technique to arrange DNA synthesized strands (commonly referred as DNA origami) on surfaces made of materials compatible with existing semiconductor manufacturing equipment [45]. The positioned DNA nano-structures can serve as scaffolds, or miniature circuit boards, for the precise assembly of components such as carbon nanotubes, nanowires, nanoribbons and nanoparticles [66]. In Fig. 9, two carbon nanotubes are precisely attached to a silicon surface by means of DNA scaffolding. Each nanotube has a different DNA strand, complementary to the DNA strands on the silicon surface. A DNA strand is composed of a sequence of nucleotides. The four possible nucleotides, adenine, guanine, thymine and cytosine, are complementary two by two, which means that there is a unique strand that matches a given DNA sequence (Fig. 8). As a result, they can only be connected in a single position and with a defined orientation.
- In a *bio-hybrid approach* [95], biological components are used as building blocks of integrated nano-devices. Several biological structures found in living organisms such as biosensors, nanoactuators, biological data storing components, can be reused in engineered or synthesized nano-devices. As an example, ATP batteries emulating the behavior of mitochondria can be an alternative energy source for bio-nano-devices. We believe that being able to directly reuse biological structures found in living organisms or to re-engineer them, will be specially useful in biomedical applications as well as the enabling technology for molecular communications [1].

The components described in Section 2 have been obtained mainly in a top-down approach. Currently, though, the major challenge in nanosensor technology is in assembling the different components and the different units into a single device. Indeed, nanobatteries and nanosensor units, for example, have been developed and tested under very strict laboratory conditions, but manufacturing an integrated device with them is still an open challenge. We believe that while top-down integration techniques will predominate at least for one more decade, novel bottom-up procedures, such as an evolution of DNA scaffolding, will be the way to obtain integrated nano-devices with higher complexity. In Fig. 2, our vision of an integrated nanosensor device is shown. This nanosensor is able to sense, process, store and communicate different types of events, while harvesting mechanical and vibrational energy from the medium, and all of these occupying approximately 10 μm^2. As a reference for the reader, the average size of a human cell is also in the order of ten square micrometers.

4. Applications of wireless nanosensor networks

The applications of WNSNs can be classified in four main groups: biomedical, environmental, industrial, and military applications.

4.1. *Biomedical applications*

A large number of direct applications of wireless nanosensor networks is in the biomedical field. The nanoscale is the natural domain of molecules, proteins, DNA, organelles and the major components of cells [55] (Fig. 7). Biological nanosensors provide an interface between biological phenomena and electronic nano-devices. These are some of the envisaged applications of nanosensor networks.

- *Health monitoring systems*: sodium, glucose and other ions in blood [19], cholesterol [49], cancer biomarkers [86] or the presence of different infectious agents [82] can be monitored by means of nanosensors. For

example, tattoo-like sensors [19] can be used to monitor the glucose level in blood, releasing diabetic people from having to prick their fingers several times a day. Different nanosensors distributed around the body, defining a *human body nanosensor network* (Fig. 10), could be used to gather data about the level of different substances. More interestingly, a wireless interface between these nanosensors and a micro-device such as a cellphone or specialized medical equipment could be used to collect all these data and forward them to the healthcare provider.
- *Drug delivery systems*: while nanosensors can be used to monitor the level of a specific substance, nanoactuators can be used to release a specific drug in unreachable locations of our body [22]. For example, we think of a distributed network of nanosensors and nanoactuators which decide whether to release or not a given drug to control the intra-cranial pressure, a chemical compound to dissolve a clot in an artery, or an engineered antibody to improve the immunologic system of humans in front of new diseases. Rather than just releasing a fixed amount of the drug, by means of coordination among nanosensors and nanoactuators, cooperative schemes can be used, in which the decisions to act or not are taken *on the fly*. At the same time, all these data can be collected and remotely monitored by a medical doctor or healthcare provider.

4.2. Environmental applications

The high sensibility and the large diversity of chemical nanosensors can be exploited in several environmental applications that are otherwise unfeasible with current technologies.

- *Plants monitoring systems*: trees, herbs, or bushes, release several chemical composites to the air in order to attract the natural predators of the insects which are attacking them, or to regulate their blooming among different plantations, amongst others [30,65,29]. Chemical nanosensors can be used to detect the chemical compounds that are being released and exchanged between plants. A network of nanosensors can be build up around classical sensor devices already deployed in agriculture fields to monitor these ongoing processes, in addition to other classical physical magnitudes such as humidity or temperature.
- *Plagues defeating systems*: complementary to plants monitoring, nanosensors and nanoactuators can be used in a coordinated manner to trigger, increase or abort natural processes between plants. For example, instead of using synthetic chemical products to fight insect plagues, we think of a network of chemical nanoactuators which release the same natural volatiles able to attract natural predators of worms [65], amongst others. The release of these substances can be remotely triggered from a command center that interacts with microscale sensor devices and these on their turn activate the nanoactuators.

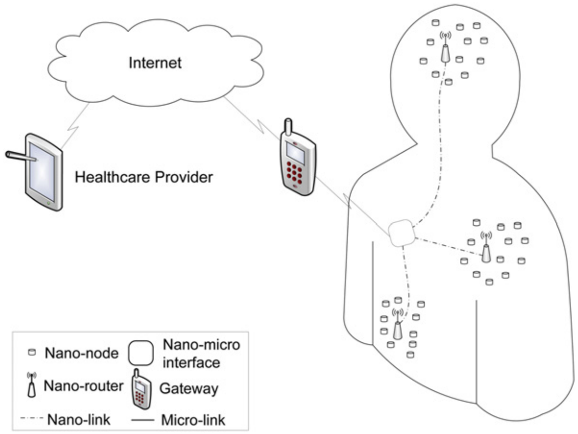


Fig. 10. Network architecture for WNSNs in healthcare applications.

4.3. Industrial and consumer goods applications

The applications of nanotechnology in the development of new industrial and consumer goods range from flexible and stretchable electronic devices [69] to new functionalized nanomaterials for intelligent self-cleaning anti-microbial textiles [85]. For the specific case of WNSNs, these are some of some new applications that we envision:

- *Ultrahigh sensitivity touch surfaces*: physical nanosensors can be used in a distributed manner to develop touch surfaces with high sensitivity and precision, and covering potentially larger areas than by means of existing solutions. For example, touch nanosensors [13] can be randomly placed and fixed over a relatively large surface such as a desk or a conference table. A calibration process coordinated by a nano-controller could be used to define the boundaries and the position of the different nanosensor devices before their utilization. In addition, this surface could be self-powered, harvesting the energy from the friction of the user movements.
- *Haptic interfaces*: haptic technology interfaces with the user by the sense of touch. Physical nanosensors and nanoactuators can be used to enhance remote controls of complex machinery, amongst others. Similarly to the concept of distributed touch surfaces, a wireless network of nanosensors and nanoactuators could be used to enhance a peripheral such as a keyboard in cellphones or ultra-portable laptops. While a wired option may be possible, the potential of unwired nanosensors and nanoactuators is clearly higher [34].
- *Future interconnected office*: the interconnection of nanosensor and nanoactuator devices with existing communication networks and ultimately Internet enables new interesting applications that will impact also in the way we work. For example, in an interconnected office (Fig. 11), every single element can be provided of a nanosensor device which allows them to be permanently connected to the Internet. As a result, a user can keep track of all its professional and personal belongings in an effortless fashion. Convenience and seamless deployment will lead us to the integration and use of nanosensor devices in every single device.

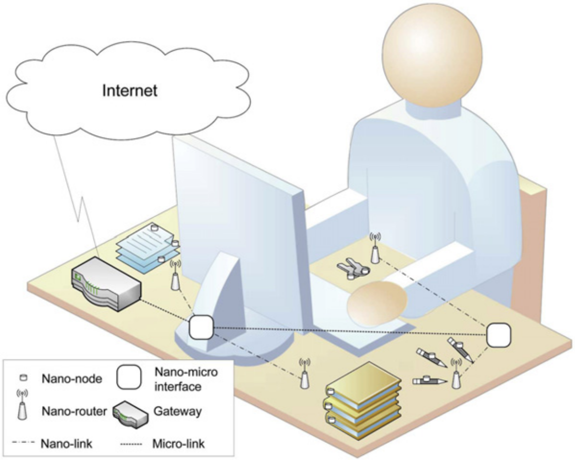


Fig. 11. Network architecture for WNSNs in the interconnected office.

4.4. Military and defense applications

Communication among nanosensors open up a range of realistic applications of nanotechnology in the military field. Amongst these we envision the following:

- *Nuclear, biological and chemical (NBC) defenses*: chemical and biological nanosensors can be used to detect harmful chemicals and biological weapons in a distributed manner. One of the main benefits of using nanosensors rather than classical chemical sensors is that the presence of a chemical composite can be detected in a concentration as low as one molecule. However, taking into account that these sensors need direct contact with the molecules, having a network with a very large number of nanosensor nodes is necessary. In addition, by means of chemical nanosensors it is possible to recover the molecular composition of a room or the battlefield without requiring external and large equipment such as the devices used for spectroscopy. Our vision is that by means of *passive spectroscopy*, a WNSN will be able to converge the information of the molecular composition of the air in a specific location to a micro- or macro-device in a very short time.
- *Damage detection systems*: physical nanosensors can be used to detect very small cracks in textiles, civil structures, vehicles and even rockets. By having a network of nanosensors distributed over the structure that has to be monitored and by means of interaction with micro-devices, WNSNs can be used to detect the origin of larger problems in functionalized textiles, soldiers' armor, or bridges, amongst others.

5. Wireless nanosensor network architectures

The interconnection of nanosensor and nanoactuator devices, existing wireless communication networks and ultimately the Internet, requires the development of new networking architectures. In Figs. 10 and 11, we illustrate the network architecture for two of the aforementioned applications, namely, intrabody nanosensor networks for health monitoring, and the future interconnected office.

Regardless of the final application, we identify the following components in the network architecture of WNSNs:

- *Nano-nodes:* these are the nanosensor and nanoactuator devices explained in Section 2. They are able to perform simple computation, have limited memory, and can only transmit over very short distances, mainly because of their reduced energy and limited communication capabilities. Biological nanosensor nodes inside the human body and nanomachines with communication capabilities integrated in all types of things such as books, keys, or paper folders are good examples of nano-nodes.
- *Nano-routers:* these nano-devices have comparatively larger computational resources than nano-nodes and are suitable for aggregating information coming from limited nanosensor devices. In addition, nano-routers can also control the behavior of nano-nodes by exchanging very simple control commands (on/off, sleep, read value, etc.). However, this increase in capabilities involves an increase in their size, and this makes their deployment more invasive.
- *Nano-micro interface devices:* these are able to aggregate the information coming from nano-routers, to convey it to the microscale, and vice versa. We think of nano-micro interfaces as hybrid devices able both to communicate in the nanoscale using nanocommunication techniques and to use classical communication paradigms in conventional communication networks.
- *Gateway:* this device will enable the remote control of the nanosensor network over the Internet. For example, in a intrabody network scenario, an advanced cellphone can forward the information it receives from a nano-micro interface in our wrist to our healthcare provider. In the interconnected office, a modem-router can provide this functionality.

Despite the interconnection of microscale devices, the development of gateways and the network management over the Internet are open research areas per se, in the remaining of this paper we focus on the communication challenges among nanosensor devices.

6. Communication challenges in wireless nanosensor networks

WNSNs are a very exciting research area because they are the enabling technology of many applications that will impact our society and change our daily lives. Currently, though, they are still at a very early stage. In the following, we discuss the main research challenges for communication among nanosensor devices.

6.1. Why electromagnetic nanosensor networks in the terahertz band?

We think of two possible frequency bands of operation of wireless nanosensor networks, namely, the terahertz band and the upper part of the megahertz band. As we discussed in Section 2.6, the terahertz band will be enabled by the use of novel nano-antennas, whereas the megahertz frequency range can be realized by means of an electromechanical nano-transceiver. Initially, it may seem that by using the latter approach and transmitting at lower frequencies, nanosensor devices would be able to communicate over longer distances. However, the energy efficiency of the process to mechanically generate EM waves in a nano-device is predictably very low. For this, we believe that nanosensor devices will not communicate among themselves by using the megahertz frequency range. Instead, our vision is that this band can be used to remotely control the nanosensor devices from the micro- and macroscale. This idea stems from the fact that EM waves in the megahertz range can be easily generated by using classical transmitters in the macro-domain. Higher energy waves can be used to control thousands or even millions of nanosensor devices deployed in very large areas. In that case, it will be necessary to develop accurate channel models as well as communication protocols for wireless macro–nano interfaces.

For the above reasons, we believe that nanosensor devices will potentially communicate among them in the terahertz band (0.1–10.0 THz). While the frequency regions immediately below and above this band (the microwaves and the far infrared, respectively) have been extensively investigated, this is one of the least-explored frequency zones in the EM spectrum. Therefore, the first research challenge for nanosensor device communication is to develop new channel models for the terahertz band.

6.2. *Terahertz channel modeling*

The few terahertz channel models existing to date [64,98] are aimed to characterize the communication between devices that are several meters far. On the contrary, thinking of nanoscale communications for nanosensor networks, there is a need to understand and model the terahertz channel in the very short range, i.e., for distances much below 1 m. In the following, the main characteristics of the terahertz channel in the nanoscale are reviewed.

6.2.1. *Path-loss*

The total path-loss for a traveling wave in the terahertz band is defined as the addition of the spreading loss and the molecular absorption loss [40]. The spreading loss accounts for the attenuation due to the expansion of the wave as it propagates through the medium, and it depends only on the signal frequency and the transmission distance. The absorption loss accounts for the attenuation that a propagating wave will suffer because of molecular absorption, i.e., the process by which part of the wave energy is converted into internal kinetic energy to some of the molecules which are found in the medium [23]. This depends on the concentration and the particular mixture of molecules encountered along the path. Different types of molecules have different resonant frequencies and, in addition, the absorption at each resonance is not confided to a single center frequency, but spread over a range of frequencies. As a result, the terahertz channel is very frequency selective.

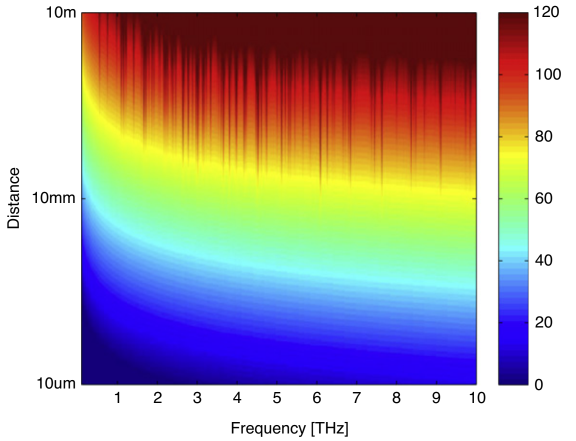


Fig. 12. Total path-loss in dB as a function of frequency and distance in a standard medium with 1% of water vapor molecules (the values for path-loss have been truncated at 120 dB to avoid masking relevant transmission windows in the short range).

In Fig. 12, the total path-loss for an electromagnetic wave in the terahertz band is shown as a function of both frequency (*x*-axis) and distance (*y*-axis), in standard room conditions (pressure 1 atm, temperature 296 K) with 1% of water molecules. This figure has been obtained using a new model for the nanoscale terahertz channel introduced in [40]. Due to the spreading loss, the total path-loss increases with both distance and frequency independently of the molecular composition of the channel, similarly to conventional communication models in the megahertz or few gigahertz frequency ranges. However, the presence of several molecules along the path, and specially water vapor, defines several peaks of attenuation for distances above a few tens of millimeters.

6.2.2. *Noise*

The ambient noise in the terahertz channel is mainly contributed by the molecular noise. The absorption from molecules present in the medium does not only attenuate the transmitted signal, but it also introduces noise [23]. The equivalent noise temperature at the receiver will be determined by the number and the particular mixture of molecules found along the path. In addition, the molecular noise is neither Gaussian nor white. Indeed, because of the different resonant frequencies of each type of molecules, the power spectral density of noise is not flat, but has several peaks. In addition, this type of noise will only appear when transmitting, i.e., there will be no noise unless the channel is being used.

In Fig. 13, the molecular noise temperature in Kelvin created by an electromagnetic wave in the terahertz band is shown as a function of both frequency (*x*-axis) and distance (*y*-axis), in standard room conditions (pressure 1 atm, temperature 296 K) with 1% of water molecules. This figure has been obtained using a new model for the nanoscale terahertz channel introduced in [40]. The molecular noise will only become significant for transmission distances above a few tens of millimeters.

6.2.3. *Bandwidth and channel capacity*

Molecular absorption will also determine the usable bandwidth of the terahertz channel. Therefore, the available bandwidth will depend on the molecular composition of the channel and the transmission distance [40].

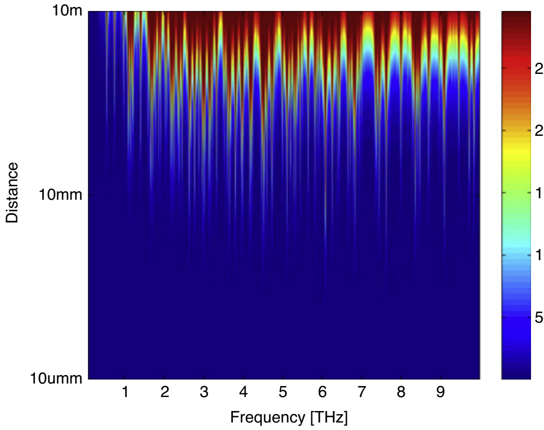


Fig. 13. Noise temperature T in Kelvin as a function of frequency and distance in a standard medium with 1% of water vapor molecules.

Within a WNSN, it is unlikely to achieve single-hop transmission distances above a few tens of millimeters. Within this range, the available bandwidth is almost the entire band, ranging from a few hundreds of gigahertz to almost ten terahertz. As a result, the predicted channel capacity of wireless nanosensor networks in the terahertz band is promisingly very large, in the order of a few terabits per second [40].

We envision different ways in which nanosensor devices can exploit this very large capacity supported by the terahertz channel. First, the amount of information that nanosensors may need to transmit from the nanoscale is also potentially very large. Nanosensors are envisioned to transmit information regarding every single molecule present in a medium or composing a material, generating billions of events that need to be notified. Second, the expected density of nanosensors willing to communicate is also very high. A very large bandwidth will allow efficient and simple multiple access schemes, specially suited for nanosensor devices. The challenge in this case will be in developing energy efficiency and simple communication mechanisms able to exploit these properties.

6.2.4. Additional channel effects: multi-path propagation and nanoparticle scattering

In addition to very high path-loss and molecular noise, multi-path fading and nanoparticle scattering affect the signal propagation:

- *Multi-path fading*: depending on the scenario in which nanosensor devices will be deployed, multiple copies of the transmitted signal will reach the receiver. The combination of these copies will result in oscillations of the power detected in reception. The amplitude of each reflection will depend on the distance that it has traveled and the type of material, shape and roughness of the surface on which it has been reflected. For example, common materials found in an office, or even the human skin, have non-negligible roughness that can damage the amplitude and phase of the reflected signal. Therefore, in order to properly account for these multiple reflections and develop new shadow fading models, it will be necessary to, first, characterize the reflection coefficients from common materials found in the envisaged scenarios and, second, use adequate models for scattering from rough surfaces. Some initial studies have been conducted in [63,62], but a particularization for the nanoscale is missing.
- *Particle scattering*: molecules and other particles in the medium can create scattering effects on the transmitted signal. These effects can be considered almost negligible in some applications, but can drastically affect the communication performance between nanosensors in other situations. For example, the diameter of a water vapor molecule is around 0.28 nm, more than 5 orders of magnitude below the wavelength of a signal in the terahertz frequency range (between 30 and 3000 μm). The scattering by particles much smaller than the signal wavelength is known as Rayleigh scattering [23] and can be taken into account as an additional power loss. However, when thinking of a scenario containing synthesized nano-structures, magnetic nanoparticles or nanoshells, it will be necessary to understand, model and account for their scattering of the transmitted wave. These models do not exist to date.

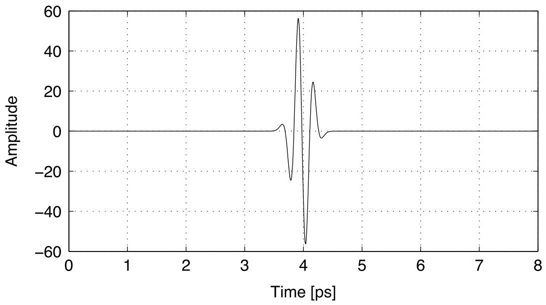


Fig. 14. Fifth derivative of a 0.1 ps long Gaussian pulse.

6.3. Information encoding and modulation in electromagnetic wireless nanosensor networks

Nanosensor devices need novel information encoding and modulation techniques able to exploit the huge bandwidth provided by the terahertz channel, while still remaining feasible for their hardware limitations. As an alternative to complex modulations, we envision the use of sub-picosecond-long pulses for communication among nanosensor devices (Fig. 14). The power of a sub-picosecond-long pulse is contained within the terahertz frequency band and it can be obtained by simple combination of graphene delay lines and a nano-capacitor [71]. In addition, by transmitting these pulses distributed over time rather than in a single continuous packet or burst (Fig. 15), the requirements on the power unit of nanosensor devices are also relaxed. Note that the transmission of short pulses is also at the basis of Impulse Radio Ultra-Wide-Band (IR-UWB) systems [35]. In that case, tiny bursts of nanosecond-long pulses are used with a time between bursts in the order of hundreds of nanoseconds. Orthogonal time hopping

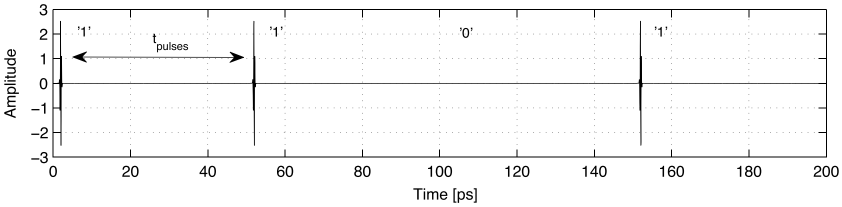


Fig. 15. Pico-pulse-based communications. The time between pulses, $t_{pulses} = 50$ ps, is much longer than the pulse length, 0.1 ps in this case.

sequences are used to interleave different users in a synchronous manner. For nanosensor networks, the complexity of such advanced systems is totally out of scope.

The use of pulses rather than continuous waves requires novel modulation techniques. Conventionally, the information in pulse-based communication is encoded either in (i) the amplitude of the transmitted pulses (Pulse Amplitude Modulation), (ii) the temporal position of the pulse (Pulse Position Modulation), (iii) the pulse width (Pulse Width Modulation), (iv) the rate of pulses (Pulse Rate Modulation), or (v) in the time between consecutive pulses (paradigm known as communication through silence [103]). However, these are not directly suitable for communication among nanosensor devices due to several reasons. First, the terahertz channel is very frequency selective, thus, placing the information in the pulse shape is not recommended. Second, placing the information in the temporal position of pulses requires accurate synchronization between nanosensor devices, which does not seem feasible due to the random nature of WNSNs. Third, the pulse width is fixed provided that we want to stay in the terahertz band. For all these, it is quite clear that we need new ways to encode the information.

Our vision is that nanosensors need to detect the presence or absence of these pulses by doing some type of energy detection. For example, they can transmit a pulse to represent a logic one and be silent to transmit a logic zero. Detecting a very low energy pulse using for example a matched filter or a correlator requires again accurate sampling and synchronization. However, this requirement can be relaxed by transmitting multiple pulses in a burst rather than a single pulse. Parameters such as the energy per pulse, the number of pulses in a burst, or the time between consecutive pulses, need to be optimized in a cross-layer fashion starting from the hardware limitations and the channel shape.

6.4. Protocols for electromagnetic wireless nanosensor networks

While there are still major open issues in relation to the communication between just two nanosensor nodes, in the following we provide our initial ideas for the networking of several nano-nodes.

6.4.1. Channel access control

Different channel access control mechanisms for WNSNs will be defined depending on how the information is encoded. For example, carrier sensing based MAC protocols (e.g., CSMA and all its variations) cannot be used in pulse-based communications because there is no carrier signal to sense. However, in this specific case, the fact that the information is transmitted using very short pulses potentially reduces the chances of having a collision between nanosensor devices trying to access the channel at the same time. In addition, if we allow the time between pulses to be much longer than the pulse duration, it is possible to interleave different pulse streams.

We believe that nanosensor devices will be able to track different users interleaved in time. Simply stated, a nano-device will start sending an encoded pulse stream when it needs to transmit. Nodes in the transmission range will be able to detect this first pulse with a given probability of detection. If the time between pulses is fixed and known by all the network members, after the detection of the first pulse, nano-devices will be able to predict when the next pulse is coming. In the meantime, they can decide to transmit their own stream or even to follow different streams from other users. This is a high level simplification of what a channel access control mechanism for WNSNs can look like.

6.4.2. Sensing-aware information routing

Communication protocols, aware of the properties of the physical channel, using power and bandwidth control, and exploiting the interdependencies between different layers in the protocol stack, have become very popular in different types of networks, from sensor networks to cognitive radio networks. WNSNs are not an exception, and there actually more *ingredients* that should be taken into account in a design of communication protocols. Moreover, the simplicity of nanosensor nodes is far from the complexity of classical layered approaches to protocol design.

As emphasized in Section 2.1, both carbon nanotubes and graphene nanoribbons have all their atoms exposed to the medium, and this is what makes them very good candidates for sensing applications. At the same time, nano-antennas for the terahertz band (and electromechanically resonating nanotubes too) are made of the same material, which means that the medium will also affect their electromagnetic properties. For example, as described in [93,48], different types of molecules can change the local electric charge distribution in a graphene nanoribbon. This change in the electron local density modifies the wave propagation velocity in the nano-antenna. The wave propagation velocity determines the resonant frequency of the antenna. Consequently:

- If the nano-antenna has been designed considering that there are no adsorbates on the nanoribbon or the

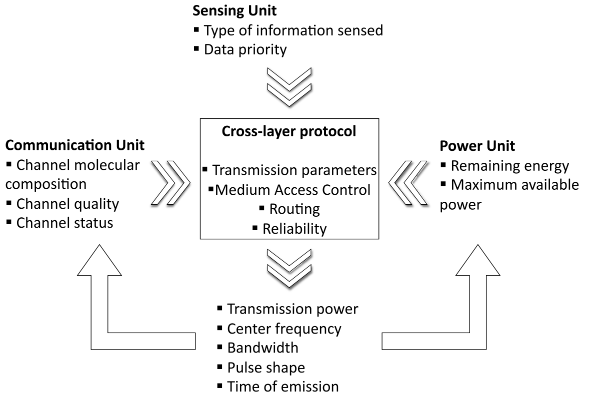


Fig. 16. Sensing-aware protocol design for WNSNs.

nanotube, the presence of external molecules affecting the wave propagation velocity in the antenna will result in a lower radiation efficiency, or in other words, in an additional power loss.

- If the nano-antenna dimensions have been designed assuming the presence of adsorbates on the nanoribbon or the nanotube, only when these molecules are present, the antenna will be able to efficiently radiate the transmitted signal. Note than in both cases and due to the reciprocity principle in antenna theory [6], this effect is also present in reception.

There are different solutions to this problem, such as covering the antenna with an inert chemical compound which does not alter the electron movements within the nano-structure and isolates the antenna from the medium. However, coating the antenna with this type of materials can introduce an additional power loss in the transmitted signal.

Our vision is that, rather than trying to prevent this effect, we can try to use it for our benefit. We do not need to go against the channel, but to exploit its possibilities. Indeed, the effects of molecules in the nanomaterials behavior can be seen as a natural way to modulate a carrier frequency with chemical information. For example, a nanosensor covered with a specific type of molecules such as nitric oxide (NH_3) or carbon monoxide (CO) can detect that by means of its sensing unit [93] and correspondingly adapt the transmission frequency to the new resonant frequency of its antenna. Nanosensors detecting the same type of molecules will also work in the same frequency channel. If only one sensor detects these specific molecules, it may be ignored or not, depending on how the sensors are programmed. One option is to consider this event as a false detection and to not further forward the message. Another option is to consider this as a high priority channel, i.e., all the events coming signaled at the specific frequency corresponding to the presence of a given type of molecules, will have a higher priority and must be forwarded as soon as possible to the command center or sink.

For all these reasons, a cross-layer protocol for nanosensor networks cannot simply ignore the type of data that is being measured. Besides power and bandwidth awareness, the nanosensor needs to be aware of the information that is being measured and consequently adapt the properties of its radio unit. In addition, the priority of the information that is being sensed can trigger special protocols, affecting how the entire network behaves. In Fig. 16, we show the relation between the different units integrating a nanosensor device and a sensing-aware cross-layer protocol for WNSNs.

6.4.3. *Reliability issues in electromagnetic wireless nanosensor networks*

End-to-end reliability in WNSNs has to be guaranteed both for the messages going from a command center to the nanosensor devices, as well as for the packets coming from the nanosensors to a common sink. This is specially important in the biomedical applications of wireless nanosensor networks. Different aspects that can affect the network reliability include:

- *Nanosensor device failure*: the physical properties of nanomaterials, specially the strength of carbon-based structures, ensures that nanosensor devices will not be easily physically damaged. However, we cannot state the same about their robustness against environmental and chemical phenomena.
- *Transient molecular interference*: a sudden burst of molecules can create temporal disconnections of the network at different points. If this is only a local effect on some nanosensor devices, a routing protocol can determine an alternative path. These molecules can affect single nanosensor devices, some parts of the network or the entire system.

We envision different solutions for these challenges. For example, a naive option to deal with nanosensor device failure would be to increase the number of nanosensor devices covering the same area. However, increasing the nanosensor device density will bring more problems to the MAC and routing protocols, at least. When it comes to transient molecular interference, more complex solutions are needed. For example, absorbing molecules will create peaks of attenuation but several transmission windows with contained path-loss may still be usable. Based on this, we can think of sensing-aware protocols in which nanosensor devices dynamically choose the transmission window. If multi-band nano-antennas are developed, or more than one nano-antenna can be integrated in a single nano-device, new cognitive radio protocols can be developed.

6.4.4. *A new notion of mobility*

The tiny dimensions of nanosensors makes them suitable for exploring unreachable locations with unprecedented resolution. However, they also make them vulnerable in front of any kind of external force. For example, nanosensor devices randomly deployed in an open field can be easily taken away by an air flow, or biological nanosensors can be swept away by a body fluid, for example. This may be seen as a shortcoming but can also be exploited in a beneficial way [33].

There are several applications in which mobility of nanosensors can make the difference. For example, we can think of a scenario with a fixed wall-mounted sink and thousands of nanosensors being periodically released in the air. Assuming a short sensing time and by taking into account the very large bandwidth supported by the terahertz channel, nanosensors will be able to send the information to the sink as they keep moving wherever the wind takes them. Similarly, obviating for the time being the biocompatibility of nanosensors, a set of nanosensors can be released in the blood stream of our body. A fixed sink can gather the information of a moving sensor in a periodic fashion, every time that the sensor passes by.

7. Conclusions

Wireless nanosensor networks will have a great impact in almost every field of our society ranging from healthcare to homeland security and environmental protection. Enabling the communication among nanosensors is still an unsolved challenge. In this paper, we have focused on the electromagnetic option for communication among nanosensors, nanoactuators and nano-devices in general. We have introduced our notion of nanosensor device and discussed the state of the art and the implementation challenges of each nano-component in an integrated nanosensor device. Despite several nanosensors, nanoactuators, nano-power systems or nano-processors are being prototyped and developed, there is no integrated nanosensor device for the time being.

The use of novel nanomaterials to build nano-antennas, nano-transceivers and nano-processors has pointed us to the terahertz band as the natural domain of operation of nanosensor devices. This frequency range supports very high transmission bandwidths in the short range. Based on this and the hardware specifications of nanosensor devices, we have discussed the possibility to use sub-picosecond-long pulses for communication in the nanoscale. This introduces several research challenges starting from how to encode the information by using very short pulses or how to manage the channel access among several nanosensor devices, to how to guarantee the end-to-end reliability in nanosensor networks.

Despite nanosensor devices and networks are still in their very early stage, Information and Communication Technologies (ICT) are a key player in the development of this new paradigm. Many researchers are currently engaged in developing the hardware underlying future nanosensor devices. However, novel nano-antenna designs and models, nanoscale terahertz channel models, information encoding and modulations for nanoscale networks, and protocols for nanosensor networks are contributions expected from the ICT field which will also drive the nano-device design.

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