WIRELESS NANOSENSOR NETWORKS USING GRAPHENE-BASED NANO-ANTENNAS

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ABSTRACT

Nanotechnology is enabling the development of devices in a scale ranging from oneto 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 . 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 inconcentrations as low as one part per billion the presence of different infectious agents such as virus or harmful bacteria. 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, 1. Molecular communication 2. Nano-electromagnetic communication.

Keyword: Nanotechnology, nanomaterials, nanoparticles, nanosensor.

Wireless NanoSensor Networks using Graphene-based Nano-antennas

Introduction: Nanotechnology is enabling the development of devices in a scale ranging from one to a few hundred nanometers. One of the most promising applications of these nanodevices is in the field of nanosensors. A nanosensor is not just a tiny sensor, but a device that makes use of the novel properties of nanomaterials to detect and measure new types of events in the nanoscale.

For example, nanosensors can detect and measure physical characteristics of nanostructures 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. However, the sensing range of a single nanosensor is limited to its close nano-environment and thus, many nanosensors are needed to cover significant areas or volumes. Moreover, an external device and the user interaction are necessary to read the measurements from a nanosensor.

Similarly to the way in which communication among computers enabled revolutionary applications such as the Internet, the development of an integrated nanosensor device with communication capabilities will overcome the limitations of individual nanosensors and expand their potential applications. A **Wireless NanoSensor Network (WNSN)** [1] will be able to cover larger areas, to reach unprecedented locations in a non-invasive way, and to perform in-network processing and cooperative actuation. A single nanosensor device detecting or sensing a relevant event will communicate with its neighbors and transmit the information in a multi-hop fashion to a sink or command center, which will connect with the macro-world and the final users. Furthermore, their communication capabilities will allow them to receive commands from other nanosensor devices to change their behavior or actuate,
if needed.

WNSNs have a tremendous amount of applications that span diverse fields. In the biomedical
field, biological WNSNs provide an interface between biological phenomena and electronicnanodevices, and can create novel health monitoring systems and targeted drug delivery systems, amongst others. Second, in the **environmental field**, WNSNs can be used to sense chemical compounds in agriculture fields or protected areas. Finally, in the **industrial field** they can be used to design new consumer goods or enhance existing ones, such as ultrahigh-sensitivity touch surfaces or new haptic interfaces.

Nanotechnology and Graphene:

Nanotechnology is a truly multidisciplinary field which has yielded numerous discoveries, such as **graphene** and its incredible properties. Indeed, graphene is considered essential for the development of electronic components in a scale ranging from one to a few hundreds of nanometers, such as: Nanoscale FET transistors , *Nanosensors,* Nanoactuators, Nanobatteries Nano-Antennas.

Autonomous Nano-Devices:

The integration of these nano-components in a single device, just a few micrometers in size, will result in **autonomous nano-devices** able to perform specific tasks at the nano-level, such as computing, data storing, sensing or actuation. We propose the following conceptual architecture of a nanosensor remote with communication capabilities.

Integrated Nanosensor Device:

However, in order to turn existing nanosensors into autonomous devices, which can create a network, it is necessary to provide them with additional functionalities: a power source, data storage, a processing unit and a communication module. A conceptual nanosensor device, with a size in the order of a few cubic micrometers (comparable to the size of human cells), is illustrated in Fig. 1 [1]. Despite being conceptually similar to a macroscale sensor, it should be taken into account that 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.

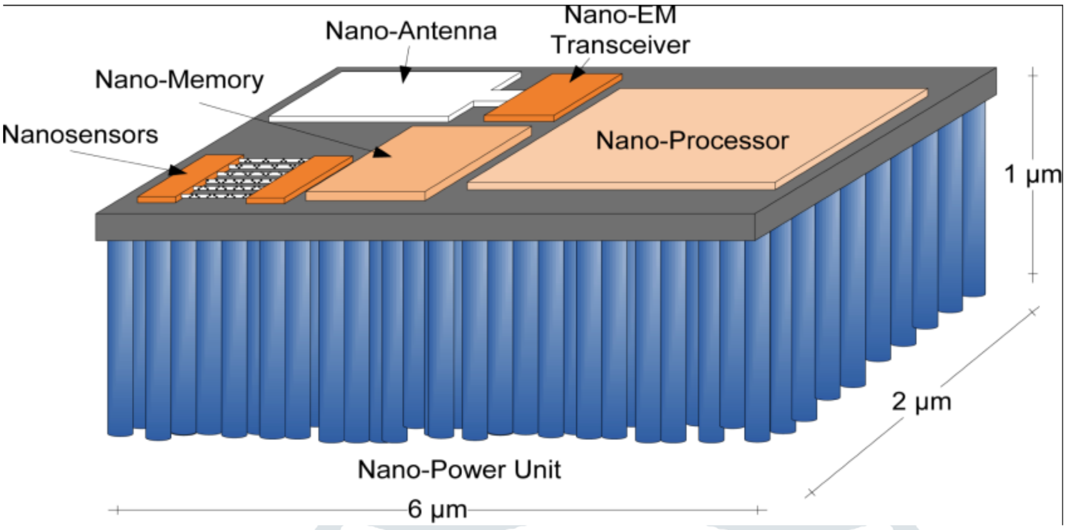


Figure 1: An integrated nanosensor device

To date, several solutions have been proposed for the different components of a nanosensor device. However, although many papers on nanosensor technologies are being published every year, it is still not clear how the communication module of nanosensor devices will operate. In light of the state of the art in small antenna design, a resonant metallic antenna operating for example at the terahertz (THz) band would have a typical dimension in the order of a few hundred micrometers. Scaling them down further to only a few micrometers would make them non-resonant and hence dramatically reduce their antenna efficiency.

However, by using materials implicitly lying in the nanoscale, such as graphene, the aforementioned requirements (i.e., small size and reasonable efficiency) can be alleviated. A few nanoantenna designs based on **carbon nanotubes** or **graphene nanoribbons** can indeed be found in the literature [2,3,4]. The main characteristic of these nanoantennas is that, because of quantum effects, the wave propagation speed in these structures is up to two orders of magnitude below the speed of light in vacuum. As a result, the expected resonant frequency of these antennas is also two orders of magnitude below that of antennas made with non-carbon materials [2]. Due to the mismatch between these two speeds of propagation, the radiation efficiency of a nanoantenna is also expectedly low, but still expectedly considerably higher than its metallic counterparts. Moreover, nanosensor devices in our envisioned WNSNs will be deployed in a range below one meter, and will incorporate a tiny nanobattery or an energy-harvesting unit. This will enable them to communicate using a very short-range and to fulfill their needs. However, the characteristics of these antennas in the very short range remain unknown.

Graphene-Based Nano-Antennas-I

Novel nanomaterials such as Carbon Nanotubes (CNTs) and Graphene Nanoribbons (GNRs) have been proposed as the building material of novel **nano-antennas**. Their development stems from the necessity of solutions which radiate in adequate frequencies. If we used the classical approach, antennas reduced to the nanoscale would radiate at extremely high frequencies, compromising the feasibility of the communication.

Graphene-Based Nano-Antennas (II)

By accounting for the quantum interactions between every single atom in the graphene structure, the transmission line properties of nano-antennas can be accurately modeled, namely, kinetic inductance *(*L*)*, quantum capacitance *(*C*)* and contact resistance *(R)*. These depend on the antenna dimensions, Fermi energy and the structure of their edge. GNR-based nano-patch (L=1 μm).

First Resonant Frequency

The radiation frequency *(f)* can be calculated if the transmission line properties are known.

$$v_p = \frac{1}{\sqrt{LC}}, \qquad \mathbf{f} = \frac{\mathbf{v_p}}{\mathbf{2L}} \qquad v_p = \text{speed of propagation}$$

The targeted breakthrough of our research is to investigate and develop novel graphene-based nanoantennas, which, in our long-term vision, will enable Wireless Nanosensor Networks. These networks are not a mere downscaled version of conventional wireless sensor networks, but there are several properties stemming from the nanoscale nature of nanosensor devices that require a complete rethinking of well-established concepts in conventional networks. We outline the main three of them next.

First of all, a graphene-based nanoantenna is not just a small antenna. Due to the peculiarities of the propagation of electrons and EM waves in graphene, the classical antenna theory needs to be revised. For example, in a graphene-based nanoantenna, the EM wave propagation speed is tightly coupled with the atomic structure of the antenna, its temperature and even on the applied energy. Thus, the dependence of parameters such as the **frequency of operation** and the **radiation efficiency** of a nanoantenna on all these parameters needs to be studied and experimentally validated.

Second, initial results on nano antenna characterization point to the terahertz band (0.1 – 10 THz). Existing communication channel models on the terahertz band are aimed at its characterization for transmission distances in the order of several meters. Hence, the effects appearing in the terahertz band (such as molecular absorption and molecular noise) in the very short range remain unknown and have not been analyzed yet. Therefore, there is the need to study the different phenomena affecting the **propagation of EM waves in the very short range** and determine the total path-loss, noise, and usable bandwidth affecting the communication among nanosensor devices. This will then allow the development of a **channel model** for short-range communications in the terahertz band.

Terahertz Propagation Model:

The terahertz band is an **unlicensed frequency range** between 100 GHz and 10 THz. The terahertz channel is mainly determined by **molecular absorption**, i.e. the conversion of the wave energy into kinetic energy in several gas molecules. It determines **path-loss** and **molecular noise,** which lead to the conclusion that the channel is **highly frequency selective.**

Theory of Scalability of Nanonetworks:

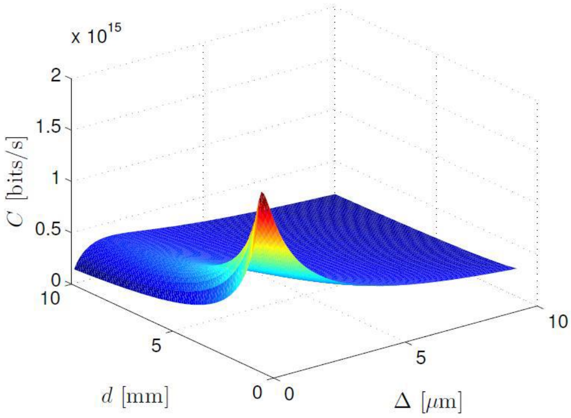
1. As the elements in nanonetworks inherently lie in the nanoscale, it is interesting to study how networks scale when its size is reduced.

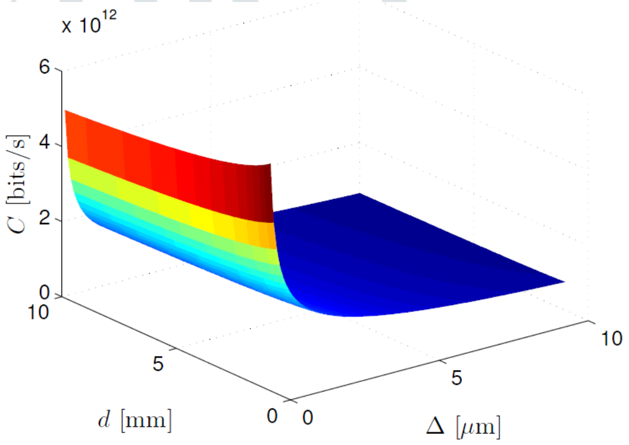
2. The dependences among **performance metrics** are analyzed:

   a. Device Size

   b.Transmission Distance

   c.Channel Capacity





Conclusion

Finally, the nanosensor devices equipped with a graphene-based nanoantenna will communicate with their neighbors and transmit the sensed information to a sink (representing

a gateway with the micro- or macro-world and the users), using a multi-hop protocol. Since nanosensor devices will have a short transmission range, many sensors will be required to create a WNSN. In consequence, each sensor will need to have a low fabrication cost, and thus the architecture of a nanosensor device must be simple. In conclusion, existing modulations, Medium Access Control (MAC) and routing protocols, such as the ones developed for traditional wireless sensor networks, cannot directly be applied to this scenario.

A third research challenge is thus to develop a **new network architecture** for WNSNs. We envisage that Wireless Nano-Sensor Networks will have a great impact in almost every field of our society, ranging from healthcare to industrial or environmental protection, and we believe that our work will pave the way for the development of this new networking paradigm.

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