Wireless NanoSensor Networks using Graphene-based Nanoantennas

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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 electronic nanodevices, 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.

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.

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.

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 nanoantenna 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.

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 NanoSensor 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.

References

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Figures

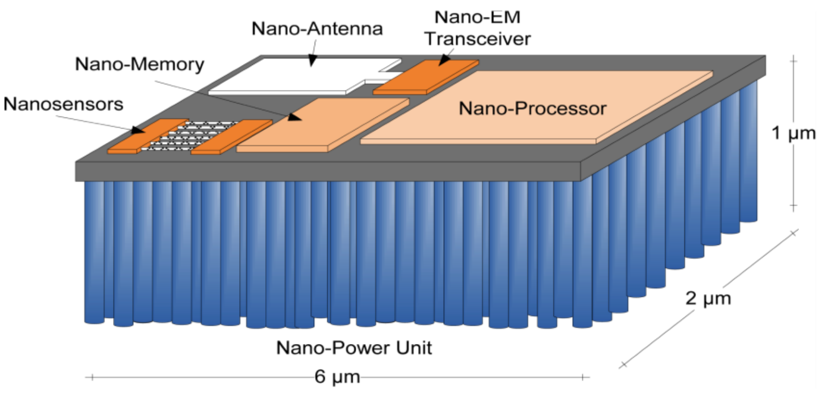

Figure 1: An integrated nanosensor device