THE INTERNET OF NANO-THINGS

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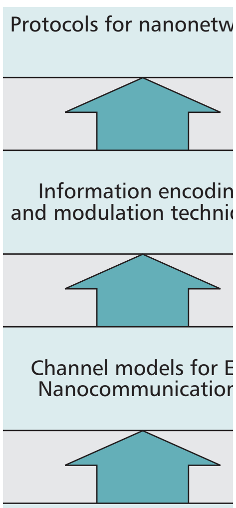

The authors discuss the state of the art in electromagnetic communication among nanoscale devices. An in-depth view is provided from the communication and information theoretic perspective

ABSTRACT

Nanotechnology promises new solutions for many applications in the biomedical, industrial and military fields as well as in consumer and industrial goods. The interconnection of nanoscale devices with existing communication networks and ultimately the Internet defines a new networking paradigm that is further referred to as the Internet of Nano-Things. Within this context, this paper discusses the state of the art in electromagnetic communication among nanoscale devices. An in-depth view is provided from the communication and information theoretic perspective, by highlighting the major research challenges in terms of channel modeling, information encoding and protocols for nanonetworks and *the Internet of Nano-Things*.

INTRODUCTION

Nanotechnology is enabling the development of devices in a scale ranging from one to a few hundred nanometers. At this scale, a nanomachine is defined as the most basic functional unit, integrated by nano-components and able to perform simple tasks such as sensing or actuation. Coordination and information sharing among several nanomachines will expand the potential applications of individual devices both in terms of complexity and range of operation [1, 2]. The resulting nanonetworks will be able to cover larger areas, to reach unprecedented locations in a non-invasive way, and to perform additional in-network processing. Moreover, the interconnection of nanoscale devices with classical networks and ultimately the Internet defines a new networking paradigm, to which we further refer as *the Internet of Nano-Things*.

Despite several papers on nano-devices and their applications are published every year, it is still not clear how nanomachines are going to communicate. For the time being, we envision two main alternatives for communication in the nanoscale, namely, molecular communication and nano-electromagnetic communication:

- *Molecular communication*: this is defined as the transmission and reception of information encoded in molecules [1, 3]. Molecular transceivers are expected to be easily integrated 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.
- *Nano-electromagnetic communication*: this is defined as the transmission and reception of electromagnetic (EM) radiation from components based on novel nanomaterials [2, 4]. The unique properties observed in these materials will decide on the specific bandwidth for emission of electromagnetic radiation, the time lag of the emission, or the magnitude of the emitted power for a given input energy.

In this article, we focus on electromagnetic communication among nano-devices and provide an in-depth view of this new networking paradigm from the communication and information theory point of view. We begin our discussion by introducing a reference architecture for the Internet of Nano-Things. We motivate the study of the Terahertz band for nano-electromagnetic communication and outline the main research challenges in terms of channel modeling, information modulation and networking protocols for nano-devices. Finally we conclude the article.

NETWORK ARCHITECTURE

The interconnection of nanomachines with existing communication networks and eventually the Internet requires the development of new network architectures. In Fig. 1, we introduce the architecture for the Internet of Nano-Things in two different applications, namely, intrabody nanonetworks for remote healthcare, and the future interconnected office:

- In *intrabody networks*, nanomachines such as nanosensors and nanoactuators deployed inside the human body are remotely controlled from the macroscale and over the Internet by an external user such as a healthcare provider. The nanoscale is the natural domain of molecules, proteins, DNA, organelles and the major components of cells. Amongst others, existing biological nanosensors and nanoactuators provide an interface between biological phenomena and electronic nano-devices [2], which can be exploited through this new networking paradigm.
- In the *interconnected office*, every single element normally found in an office and even its internal components are provided of a nano-transceiver which allows them to be permanently connected to the Internet. As a result, a user can

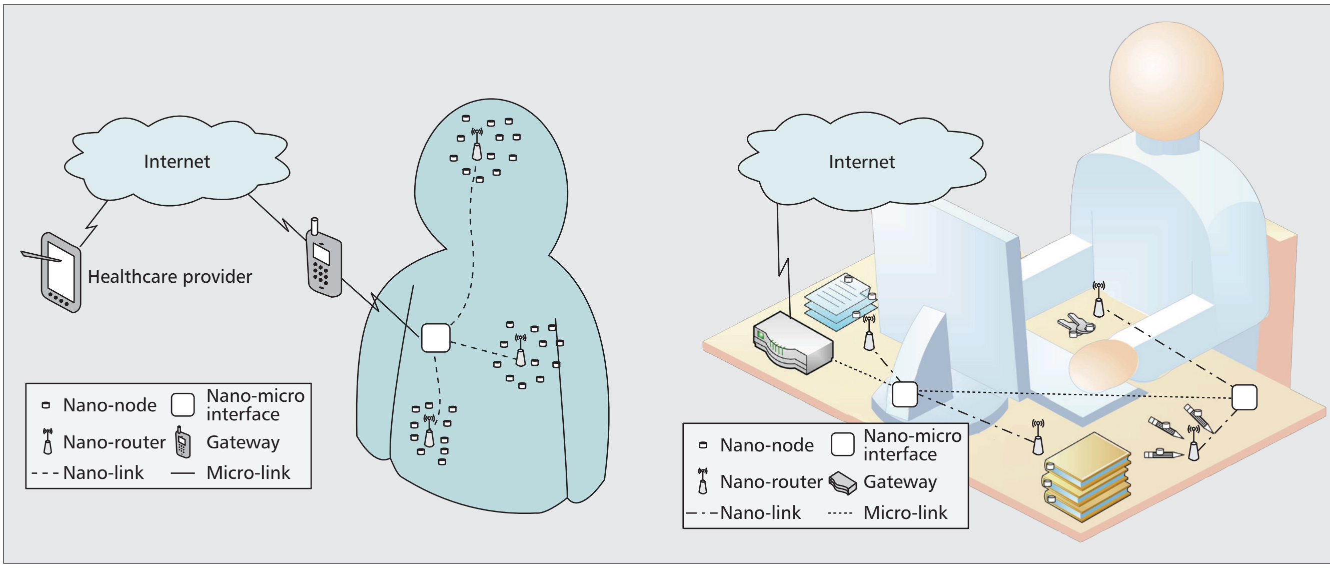

Figure 1. *Network architecture for the Internet of Nano-Things: a) Intrabody nanonetworks for healthcare applications; b) The interconnected office.*

keep track of the location and status of all its belongings in an effortless fashion. Convenience and almost seamless deployment demand for tiny and non-obtrusive devices. Amongst others, the possibility to harvest vibrational, mechanical or even EM energy from the environment [5], an ultra-low power consumption and reasonable computing capabilities, motivate the use of new nanomaterials in the development of these devices.

Regardless of the final application, we identify the following components in the network architecture of the Internet of Nano-Things:

Nano-nodes: these are the smallest and simplest nanomachines. 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 nanomachines. 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 the aforementioned nanocommunication techniques and to use classical communication paradigms in conventional communication networks.

Gateway: this device enables the remote control of the entire system over the Internet. For example, in an 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 provided this functionality.

Despite the interconnection of microscale devices, the development of gateways and the network management over the Internet are still open research areas, in the remaining of this article we mainly focus on the communication challenges among nanomachines.

Communication Challenges for Electromagnetic Nanonetworks

The Internet of Nano-Things begins at the networking of several nanomachines. Nanonetworks are not just downscaled networks, but there are several properties stemming from the nanoscale that require us to totally rethink well-established networking concepts. In the following, the main challenges from the communication perspective are discussed in a bottom-up fashion, by starting from the physical nanoscale issues affecting a single nanomachine up to the *nanonetworking protocols*. The design flow for the development of nanonetworks is shown in Fig. 2.

Frequency Band of Operation of Electromagnetic Nano-transceivers

The communication opportunities and challenges at the nanoscale are strongly determined by the frequency band of operation of future nano-transceivers and specially nano-antennas. Currently, graphene-based nano-antennas have been proposed for nanoscale communications [6, 7]. These antennas are not just mere reductions of classical antennas. Indeed, the wave propagation velocity in graphene can be up to one hundred times below the speed of light in vacuum. As a result, the resonant frequency of nano-antennas based on graphene can be up to two

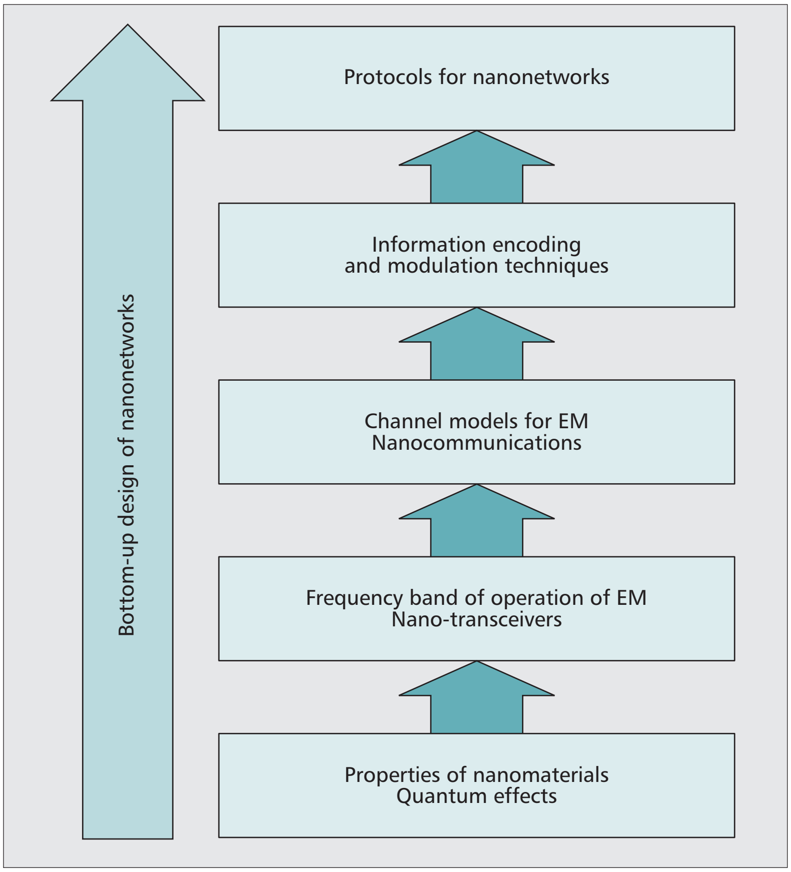

Figure 2. *Bottom-up approach to the design of nanonetworks.*

orders of magnitude below that of nano-antennas built with non-carbon materials. In particular, in [8] we determined that a 1 μm long graphene-based nano-antenna based either on a graphene nanoribbon (GNR) or carbon nanotube (CNT) can only efficiently radiate in the Terahertz range. Interestingly enough, this matches the initial predictions for the frequency of operation of graphene-based RF transistors [8].

Alternatively, it has been shown that it is possible to receive and demodulate an electromagnetic wave by using a single carbon nanotube that mechanically resonates at the wave frequency [9]. In this case, the mechanical antenna is integrated by a CNT which has one of its ends connected to a very high voltage source and the other end is left floating. When the nanotube is irradiated by an EM wave, the electrons at the free tip 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 can mechanically resonate at frequencies around a few hundreds of Megahertz.

The use of EM waves in the Megahertz range can initially be more appealing than the radiation in the Terahertz band, provided that by transmitting at lower frequencies, nanomachines could communicate over longer distances. However, the energy efficiency of the process to mechanically generate EM waves in a nano-device is predictably very low [10]. In addition, a very high-power source is needed to excite the CNT. Because of this, it does not seem technologically feasible to efficiently radiate above a few micrometers by using a mechanically resonating CNT and, thus, we envision future electromagnetic nanonetworks to operate in the Terahertz band. Nonetheless, we can still use the CNT-based nano-mechanical receiver to control the nanomachines from the macro- and micro-scale. For example, a conventional AM/FM transmitter can be used to simultaneously activate or deactivate thousands of nano-devices.

Focusing on the Terahertz band, we should emphasize that 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 electromagnetic nanonetworks is to develop new channel models for the Terahertz band.

Channel Modeling

Thinking of the applications of nanonetworks within the Internet of Nano-Things paradigm, there is a need to understand and model the Terahertz channel in the very short range, i.e., for distances much below 1 meter. In [11] we investigated the properties of the Terahertz band in terms of path-loss, noise, bandwidth and channel capacity which we are presenting briefly next.

Path-loss — The total path-loss for a traveling wave in the Terahertz band is contributed by the spreading loss and the molecular absorption loss. 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. This phenomenon 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 confined to a single center frequency, but spread over a range of frequencies. As a result, the Terahertz channel is very frequency-selective. In addition to this, scattering from nano-particles and multi-path propagation can affect the signal strength at the receiver.

Noise — The ambient noise in the Terahertz channel is mainly contributed by the molecular noise. Molecular absorption does not only attenuate the transmitted signal, but it also introduces noise. The equivalent noise temperature at the receiver is mainly determined by the number and the particular mixture of molecules found along the path and the transmission distance. The molecular noise is not white but colored. Indeed, because of the different resonant frequencies of each type of molecules, the power spectral density of noise has several peaks. Moreover, this type of noise only appears when transmitting, i.e., there will be no noise unless the channel is being used.

Bandwidth and Channel Capacity — Molecular absorption determines the usable bandwidth of the Terahertz channel. Therefore, the available bandwidth depends on the molecular composition of the channel and the transmission distance. For the very short 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 electromagnetic nanonetworks in the Terahertz band is promisingly very large, in the order of a few terabits per second. However, the very limited capabilities of individual nanomachines question the reproducibility of these results in a real implementation. In other words, the information capacity is mostly limited by the capabilities of nanomachines rather than by the channel itself. However, a very large bandwidth enables new information modulation techniques and channel sharing schemes, specially suited for simple nanomachines.

INFORMATION MODULATION

Nanomachines require new simple modulation techniques suitable for their limited hardware. Inspired by the huge bandwidth provided by the Terahertz channel, we envision a new communication paradigm based on the exchange of very short pulses, just a few femtoseconds long. The power of a femtosecond-long pulse is contained within the Terahertz frequency band and, thus, it can be radiated by a graphene-based nano-antenna. By transmitting these pulses distributed over time rather than in a single continuous packet or burst, the requirements on the power unit of nanomachines are also relaxed. Note that the transmission of short pulses is also at the basis of Impulse Radio Ultra-Wide-Band (IR-UWB) systems. In that case, tiny bursts of sub-nanosecond-long pulses are used with a time between bursts in the order of hundreds of nanoseconds. Orthogonal time hopping sequences are used to interleave different users in a synchronous manner. For nanonetworks, the complexity of such advanced systems is totally out of scope.

In pulse-based communications, the information can either modulate the amplitude of the transmitted pulses, their temporal position, their duration, the time between them or the rate at which they are transmitted. With an eye towards simplicity, we think that nanomachines can simply transmit a pulse to represent a logic one and remain silent to transmit a logic zero, i.e., by following a scheme that resembles a time spread on-off keying modulation. Detecting a very low-energy pulse requires accurate sampling and synchronization. However, this requirement can be relaxed by transmitting multiple pulses in a burst rather than a single pulse, amongst others. 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. On top of this, it will be necessary to determine what a packet is and how long it should be. Our vision is that a packet will be composed by a fixed number of symbols (pulses or silences) spaced in time, with a time between symbols much larger than the symbol duration. The reason for this comes again from the very limited power options for nanomachines.

PROTOCOLS FOR NANONETWORKS

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

Channel Sharing — Different channel access mechanisms for nanonetworks need to be defined depending on how the information is encoded. For example, carrier sensing based Medium Access Control (MAC) protocols (e.g., CSMA and all its variations) cannot be used in pulse-based communications because there is no carrier signal to sense. In addition, achieving synchronization among several nano-nodes also seems quite unlikely. Moreover, very elaborated protocols cannot be implemented in simple nanomachines.

Thinking of pulse-based communications in nanonetworks, the fact that the information is transmitted using very short pulses reduces the chances of having collisions among different nano-nodes trying to access the channel at the same time. Because of this, we think of asynchronous MAC protocols, in which a nano-node willing to send a packet can just transmit it and wait for some type of acknowledgement. In addition, if we allow the time between pulses to be much longer than the pulse duration, it can be possible to interleave different pulse streams, allowing a nanomachine to follow different user pulse streams at the same time, if feasible for its computational capabilities. Simply stated, a nano-device can start sending an encoded pulse stream when it needs to transmit. Nodes in the transmission range might 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 can 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.

Even if unlikely, collisions between femtosecond-long pulses can occur. For this, ways to detect collisions at the receiver and to report this to the transmitter need to be developed. Finally, we would like to emphasize that even the number of nanomachines may be very large, the number of neighboring nano-nodes who can potentially interfere with a specific user is not as large, mainly because of their very limited transmission power and the use of very high transmission frequencies. In addition, the amount of information that these devices may need to transmit is not that large neither. All these concepts should serve as the starting point for the development of Medium Access Control (MAC) protocols for nanonetworks.

Addressing of Nanomachines — In the Internet of Things, every single element in the network requires a unique ID. In nanonetworks and the Internet of Nano-Things, assigning a different address to every nano-node is not a simple task,

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End-to-end reliability in nanonetworks and the Internet of Nano-Things has to be guaranteed both for the messages going from a remote command center to the nano-nodes, as well as for the packets coming from the nanomachines to a common sink.

mainly due to the fact that this would require complex synchronization and coordination between nanomachines. Moreover, taking into account that every single nanonetwork will already contain thousands of nanomachines, the inter-networking of all them would require the use of very long addresses. However, some simpler and more feasible alternatives are possible. For example, taking into account the hierarchical network architecture shown in Fig. 1, we can relax the previous requirement and only force those nano-nodes coordinated by the same nano-router to have different addresses. For example, an address like {*G8.I3.R1.N4*}, can be used to refer to the nano-node 4, within the domain of the nano-router 1, connected to nano-micro interface 3, linked to gateway 8.

More interestingly, we can think of specific applications in which it is not necessary to have information from a specific nanomachine, but, for example, from a *type* of nanomachine. In particular, different type of components may have different addresses, but identical nanomachines can behave in the same way in terms of communication. This is useful when only knowledge about the presence or absence of a specific type of components is required. Another example could be in nanosensor networks. In this case, different nodes will react in the same way depending on the information that is being sensed or their internal state. This can relax the coordination requirements among nanomachines, while still supporting interesting applications. In addition, these same concepts can be used to develop new network discovery and network association protocols for nanomachines.

Information Routing — Nanomachines may have to answer to a specific query from a command center or may need to report new events in a push-based fashion. This flow of information requires the establishment of routes. Due to the very limited transmission range of nanomachines, multi-hop communication will be the standard way to communicate. We cannot even consider that every nano-node will be able to transmit directly to its closest nano-router. In addition, due to the limited resources of nanomachines and also their presumably high proneness to failure, we cannot assume that route information can be stored or remembered between transmissions.

However, if a pulse-based communication system is used, we can assume that nano-nodes may have a notion of the distance between them. As in other systems as IR-UWB, ranging can be performed by the coordinated exchange of pulses between two nodes. From this, a nano-router can assign lower logical IDs to nodes that stay closer to it. In addition, in some applications there will be no need to establish different IDs to different nodes, but, for example, the different nodes at the same distance from the nano-router will have the same ID. The neighbors of these nodes, who might not have heard the nano-router, will simply take a higher ID, and broadcast it. Further nodes will consequently take higher IDs. Routing functionalities will be also highly coupled with network discovery and association services.

Reliability Issues — End-to-end reliability in nanonetworks and the Internet of Nano-Things has to be guaranteed both for the messages going from a remote command center to the nano-nodes, as well as for the packets coming from the nanomachines to a common sink. Different aspects that can affect the network reliability include both nanomachine failure and transient molecular interference in the channel. Indeed, apart from unexpected errors in nano-nodes, a sudden burst of molecules can create temporal disconnections of the network at different points. If this is only a local effect on some nanomachines, a routing protocol can determine an alternative path. On the contrary, if this affects the entire network, little can be done. For some specific applications, a naive option can be just to increase the number of nanomachines covering the same area. However, increasing the node density can challenge the channel access or the routing of information in the network. When it comes to transient molecular interference, more complex solutions are needed. For example, absorbing molecules will create peaks of attenuation, but some transmission windows with contained path-loss may still be usable. Based on this, we can think of sensing-aware protocols in which nanomachines can sense which windows are available by means of chemical nanosensors.

Network Association and Service Discovery — In the Internet of Nano-Things, every nano-node is expected to be able to seamlessly connect to the network and at the same time inform the other devices about its presence. Taking into account the amount of nano-things that can be involved in such a network, new network association and service discovery solutions are needed. In our vision, the network hierarchy defined earlier, simplifies this task. Indeed, in a majority of applications it will not be necessary to notify the entire network when a new nano-node is in the system, but just the closer nano-router or nano-micro interface at most. This vision is compatible with the idea that when going from macro- and micro- networks to nanonetworks, we are not actually covering a larger physical area, but obtaining more information from the same object or entity, e.g., its components or its internal status, amongst others. From the network perspective, different ways to inform or control a large of nano-devices directly from the macroscale can be used by exploiting the different communication options described earlier. For example, a macro-sized network controller can periodically broadcast some network information and control information at a specific fixed frequency in the Megahertz range that can be received by nano-devices incorporating a CNT-based mechanical receiver. This does not necessary interfere with the

Conclusions

The development of nanomachines with communication capabilities and their interconnection with micro- and macro-devices will enable the Internet of Nano-Things. This new networking paradigm will have a great impact in almost every field of our society, ranging from healthcare to homeland security or environmental protection. In this article, we have introduced the reference architecture for this new paradigm and discussed the state of the art of research on electromagnetic nanonetworks. Many researchers are currently engaged in developing the hardware underlying future nanomachines. The unique properties of the nanoscale and the nature of nanonetworks require new solutions for communications that should be provided by the information and communication society. Amongst others, novel nano-antenna designs, nanoscale channel models, information encoding and modulations for nanoscale networks, and protocols for nanonetworks are contributions expected from the ICT field.

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References

[1] I. F. Akyildiz, F. Brunetti, and C. Blazquez, "Nanonetworks: A New Communication Paradigm," *Computer Networks (Elsevier) J.*, vol. 52, no. 12, Aug. 2008, pp. 2260–79.

[2] I. F. Akyildiz and J. M. Jornet, "Electromagnetic Wireless Nanosensor Networks," *Nano Communication Networks (Elsevier) J.*, vol. 1, no. 1, Mar. 2010, pp. 3–19.

[3] T. Suda et al., "Exploratory Research on Molecular Communication between Nanomachines," *Genetic and Evolutionary Computation Conf. (GECCO)*, Late Breaking Papers, June 2005.

[4] C. Rutherglen and P. Burke, "Nanoelectromagnetics: Circuit and Electromagnetic Properties of Carbon Nanotubes," *Small*, vol. 5, no. 8, Apr. 2009, pp. 884–906.

[5] Z. L. Wang, "Towards Self-Powered Nanosystems: From Nanogenerators to Nanopiezotronics," *Advanced Functional Materials*, vol. 18, no. 22, 2008, pp. 3553–67.

[6] J. M. Jornet and I. F. Akyildiz, "Graphene-Based Nano-Antennas for Electromagnetic Nanocommunications in the Terahertz Band," *Proc. 4th European Conf. Antennas and Propagation, EUCAP*, Apr. 2010, pp. 1–5.

[7] M. Rosenau da Costa, O. V. Kibis, and M. E. Portnoi, "Carbon Nanotubes as A Basis for Terahertz Emitters and Detectors," *Microelectronics J.*, vol. 40, no. 4–5, Apr. 2009, pp. 776–78.

[8] Y. M. Lin *et al.*, "100-GHz Transistors from Wafer-Scale Epitaxial Graphene," *Science*, vol. 327, no. 5966, Feb. 2010, p. 662.

[9] K. Jensen *et al.*, "Nanotube Radio," *Nano Letters*, vol. 7, no. 11, Nov. 2007, pp. 3508–11.

[10] J. Weldon, K. Jensen, and A. Zettl, "Nanomechanical Radio Transmitter," *physica status solidi (b)*, vol. 245, no. 10, Oct. 2008, pp. 2323–25.

[11] J. M. Jornet and I. F. Akyildiz, "Channel Capacity of Electromagnetic Nanonetworks in the Terahertz Band," *Proc. IEEE Int'l. Conf. Commun., ICC*, May 2010, pp. 1–6.

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