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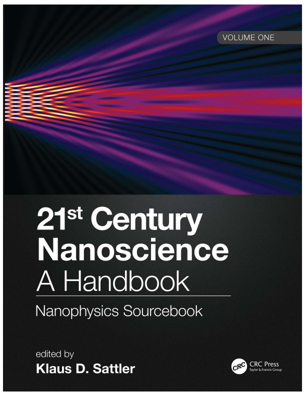

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Klaus D. Sattler

Electromagnetic Nanonetworks

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3

Electromagnetic Nanonetworks

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3.1 Introduction

Nanonetwork channels are physically separated by up to a few nanometer or/and micrometer and the nodes are assumed to be mobile and quickly deployable. Researchers are studying two types of nanonetworks: electromagnetic and molecular nanonetwork. Generally, nanomachines, act as the most basic functional unit, are able to perform very simple tasks such as computing, data storing, sensing or actuation. A set of interconnected nanomachines, sharing the same medium (e.g., the biological tissue or the fluid flow or other medium) and collaborating for the same task, form a nanonetwork. Possible applications are in healthcare, biomedical field (Freitas, 2005), environmental research (Han, Fu, & Schoch, 2008), military technology (Glenn, 2006) and industrial and consumer goods applications. Nanonetworks expand the number and range of operation envisioned for single nanomachine, since collaborative tasks like coordination, information sharing and fusion can possibly be done by different nanomachines. In molecular nanonetworks, transmission and reception of information are carried out by the motion of molecules, called information molecules. Figure 3.1 shows a typical molecular communication nanonetwork. Based on the type of molecule propagation, molecular communication techniques can be classified into walkaway-based, flow-based or diffusion-based. On the other hand, electromagnetic nanonetworks use electromagnetic waves with the framework of wireless technology. However, wiring a large number of nodes is nearly impractical because of the small size of nanomachine. Besides, it is difficult to integrate the current electromagnetic transceivers into the nanomachines because of their size and complexity. Therefore, the use of carbon structure is a possible way to develop the electronic nano-components. Recent advances in carbon and molecular electronics opened new door to generate electronic nanoscale components such as nanobatteries (Curtright, Bouwman, Wartena, & Swider-Lyons, 2004), nanoscale energy-harvesting systems (Wang, 2008), nano-memories (Bennewitz et al., 2002), logical circuitry in the nanoscale and even nano-antennas (Burke, Li, & Yu, 2006; Burke, Rutherglen, & Yu, 2006, September).

The unique properties observed in nanomaterials would choose specific bandwidths for emission of electromagnetic radiation, the time lag of the emission or the magnitude of the emitted power for a given input energy, among others (Jornet & Akyildiz, 2010a). The intrinsic behavior and characteristics of nanomachines defer from traditional devices working at the macroscale level, and distinguished features at the nanoscale level should be exposed (Akyildiz & Jornet, 2010) as shown in Figure 3.1. In this chapter, we investigate electromagnetic nanocommunications, working in the terahertz band, and foresee the possibility of transmission and reception of electromagnetic radiation from components based on nanomaterials.

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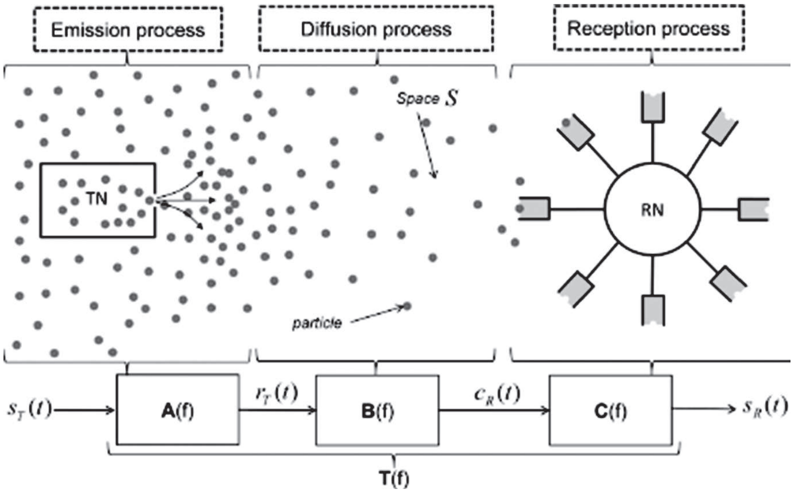

FIGURE 3.1 A typical molecular communication nanonetwork (Akyildiz, Jornet, & Pierobon, 2011).

This chapter is organized as follows. In Section 3.2, we present the challenges of electromagnetic nanocommunication. Section 3.3 describes frequency band used in electromagnetic (EM) nanonetworks. Terahertz band radiation and communication have been discussed in Section 3.4. Modulation and demodulation is presented in Section 3.5, while nanochannel and channel coding are described in Sections 3.6 and 3.7, respectively. Sections 3.8 and 3.9 describe electromagnetic nanoparticles and energy and power, respectively. We place nano-antenna in Section 3.10 and discuss routing protocol for terahertz band communication in Section 3.11. Describing sensing and receiving in Section 3.12 and we finish with the conclusions in Section 3.13.

3.2 Challenges of Electromagnetic Nanocommunication

Since in developing stage, the electromagnetic nanocommunication also has many challenges such as:

- Thermal noise and fading severely affect the communication signals
- New communication techniques must be presented e.g., sub-picosecond or femtosecond long pulses (Jornet, Pujol, & Pareta, 2012), multicarrier modulations and multi-input multi-output (MIMO) nano-antenna
- Regulation and standardization of terahertz band are required. It is imperative to model and develop the future communication standards in terahertz for a very short range such as distances much below one meter
- Information encoding techniques for electromagnetic nanocommunication are needed to be developed that are suitable for the channel characteristics
- New medium access control (MAC) and routing protocols are required to exploit the properties of the terahertz band (Akyildiz & Jornet, 2010; Jornet & Akyildiz, 2011b).

3.3 Frequency Band

Due to the limited computation skills of single nanomachine, communication and signal transmission techniques used in nanonetworks appear to be the most challenging topics. From the communication perspective, the particular characteristics observed in novel nanomaterials will decide the specific bandwidths for the emission of electromagnetic radiation, the time lag of the emission or the magnitude of the emitted power for a given input energy, among others (Jornet & Akyildiz, 2010a). So far, several alternatives have been introduced. Carbon nanotubes (CNTs) and graphene nanoribbons (GNRs) have been proposed for electromagnetic nano-antenna (Abadal et al., 2011). A graphene-based nano-antenna is not only the reduction of a classical antenna but also there are several quantum phenomena that affect the propagation of electromagnetic waves by graphene. The result is that the resonant frequency of these nanostructures can be up to two orders of magnitude below that of their nonocarbon-based counterparts. To determine the frequency band of operation of electromagnetic nanonetworks, it is obligatory to characterize the radiation properties of graphene. Up to date, reports have been found in the literature both from the radiofrequency (Jornet & Akyildiz, 2010b), (Burke et al., 2006), (Zhou, Yang, Xiao, & Li, 2003) and the optical (Da Costa, Kibis, & Portnoi, 2009), (Zhang, Xi, & Lai, 2006), (Kempa et al., 2007) perspectives. The main difference between the two options depends on the interpretation of the radiation in terms of high-frequency resonant waves radiated from nanoscale antennas or low-energy photons radiated from optical nano-emitters. However, even if the difference in origin, both approaches envisage the terahertz band (0.1–10 THz) to

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become the frequency range of operation for future nano-electromagnetic transceivers (Jornet & Akyildiz, 2010a). An architecture of nanosensor device equipped with nanosensors, nano-actuator, nano-memory, nano-antenna, nano-EM transceiver, nano-processor and nano-power unit has been presented in (Akyildiz & Jornet, 2010). When all these components are integrated, the device can sense, compute or even perform local actuation. Furthermore, the authors predict that nanosensor devices would potentially communicate among them in the terahertz band (i.e., 0.1–10.0 THz).

3.4 Terahertz Band Radiation and Communication

Falling in between infrared radiation and microwave radiation in the electromagnetic spectrum, some properties of terahertz radiation are found to be common with each of these. As in the case of infrared and microwave radiation, terahertz radiation also propagates in a line of sight and is nonionizing. Terahertz radiation can also penetrate a wide variety of nonconducting materials as microwave radiation does. Nonionizing terahertz radiation can pass through clothing, paper, cardboard, wood, masonry, plastic and ceramics. The penetration depth is, in particular, less than that of microwave radiation. Terahertz radiation has limited penetration through fog and clouds and cannot penetrate liquid water or metal. Unlike X-rays, terahertz radiation is not ionizing radiation, and its low photon energies generally do not cause any harm to living tissues and DNA (Deoxyribonucleic acid) (Choudhury, Sonde, & Jha, 2016). It can penetrate some distance through body tissue, so it is of great interest as a replacement for medical X-rays. However, due to its longer wavelength, images made using terahertz have lower resolution than X-rays and need to be enhanced.

The earth's atmosphere is a strong absorber of terahertz radiation making the range of the radiation in air limited to tens of meters. Therefore, terahertz radiation appears to be unsuitable for long-distance communications. However, at distances of the order of 10 m, the band may still allow many useful applications in imaging and construction of high bandwidth wireless networking systems, especially indoor systems (Hanson & De Maagt, 2007; Song & Nagatsuma, 2011). In addition, producing and detecting coherent terahertz radiation remain technically challenging, though inexpensive commercial sources now exist in the 0.3–1.0 THz range (the lower part of the spectrum), including gyrotrons, backward wave oscillators and resonant-tunneling diodes.

3.5 Modulation and Demodulation

One of the fundamental challenges with nanocommunication is the necessity for an appropriate modulation and channel access mechanism. So far, two main alternatives for electromagnetic communication in the nanoscale have drawn interest. First, it was experimentally demonstrated to receive and demodulate an electromagnetic wave by means of a nanoradio, i.e., an electromechanically resonating CNT, which is able to decode an amplitude or frequency-modulated wave (Atakan & Akan, 2010). Second, graphene-based nano-antennas have been analyzed as potential electromagnetic radiators in the terahertz band (Jornet & Akyildiz, 2010b). Time-hopping (TH) combined with M-ary pulse position modulation (PPM) is proposed as a modulation and multiple access scheme for multiuser nanocommunication systems (Singh, Kim, & Jung, 2018). PPM, being the most energy-efficient modulation scheme, with TH would allow nanomachiness to communicate simultaneously with greater efficiency. A modulation and channel-sharing mechanism based on the asynchronous exchange of femtosecond-long pulses transmitted through an on-off keying modulation is introduced for transmitting binary streams among nanomachines of an EM nanonetwork in (Jornet & Akyildiz, 2011c). In (Pujol, Jornet, & Pareta, 2011), a MAC protocol for EM nanonetworks built on the top of the pulse-based communication scheme for the coordination of multiple simultaneous transmissions has been presented. The proposed protocol is designed have the peculiarities of the terahertz band and is constituted by two main stages i.e., (i) the handshaking process and (ii) the transmission process. Finally, authors in (Jornet & Akyildiz, 2012) have developed an energy model for self-powered nanosensor motes, which successfully captures the correlation between the energy-harvesting and the energy-consumption processes.

Electromagnetic nanonetwork is defined as the transmission and reception of electromagnetic radiation from nanoscale components (Rutherglen & Burke, 2009). Moreover, the particular application for which the nanonetworks will be deployed limits the choice on the particular type of nanocommunication. For the time being, several alternatives have been introduced. CNTs and GNRs have been proposed in (Abadal et al., 2011) for electromagnetic nano-antenna. A graphene-based nano-antenna is not only the reduction of a classical antenna but also there are several quantum phenomena that affect the propagation of electromagnetic waves on graphene. The resonant frequency of these nanostructures can be up to two orders of magnitude below that of their noncarbon-based counterparts. However, their radiation efficiency can also be impaired because of this phenomenon. Second, CNTs have also been proposed as the basis of an electromechanical nano-transceiver or nano-radio (Jensen, Weldon, Garcia, & Zettl, 2007), able to modulate and demodulate an electromagnetic wave by means of mechanical resonation.

3.6 Nano-channel

The nanonetwork channels are physically separated by up to a few nano- or/and micrometer. For nanosensor networks, the main challenges of electromagnetic nanocommunications are expressed in terms of terahertz channel modeling, information encoding and protocols. A physical channel

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model for wireless communication in the terahertz band has been introduced in (Jornet & Akyildiz, 2011b). The authors compute the signal path loss, molecular absorption noise and, ultimately, the channel capacity of EM nanonetworks. Nanomachines working in terahertz band can theoretically have a sufficiently small size that they can be inserted into the human body (Pirmagomedov, Hudoev, Kirichek, Koucheryavy, & Glushakov, 2016). Major drawback of electromagnetic waves in the terahertz band has high losses in the tissues and body fluids of microorganism. During signal propagation in several millimeters, the losses in blood are about 120 dB, in skin – about 90 dB and in fat – about 70 dB (Yang et al., 2015). Therefore, for a distance of a couple of millimeters, the usage of repeaters is required for communication among transceiver nanomachines. The propagation model proposed in (Piro et al., 2015) characterized the performance of terahertz communication in human tissue considering the attenuation of EM waves in human skin tissues. They deduced channel capacity and communication ranges for different physical transmission environment parameters. Path loss and molecular absorption noise temperature were also obtained utilizing optical parameters of human skin tissues and were verified through extensive experimental tests. In addition, SimpleNano, a channel model for wireless nanosensor networks (WNSN) that is capable of transmitting in the terahertz range where a log-distance path loss model together with random attenuation was approximated in media such as the human body (Javed & Naqvi, 2013).

3.7 Channel Coding

Severe path loss and molecular absorption loss occur in electromagnetic communication in terahertz band. Channel coding plays an important role to detect and correct transmission errors. A detailed description of the channel codes has been reported in (Jornet, 2014a). A coding scheme for the purpose of interference mitigation was presented in (Jornet, 2014b). The minimum energy codes for nanonetworks were also introduced in (Chi, Zhu, Jiang, & Tian, 2013). The information capacity is always limited in the existing coding methods, and the network resource is not utilized adequately (Chi et al., 2013; Jornet, 2014b). However, the requirement of high-information data rate has drastically increased in the last three decades (Yao et al., 2015). For instance, wireless data rates have doubled every 18 months and almost approaching the capacity of wired communication systems (Akyildiz, Jornet, & Han, 2014). So it is obligatory to optimize the nanonetworks to improve the network information capacity.

3.8 Electromagnetic Nanoparticles

The fabrication of nanostructure devices received too much interest in the last couple of years. Optical properties of metallic nanoparticles are observed to be very much appropriate for biomedical applications (Dykman & Khlebtsov, 2012). For instance, depending on the size, shape, geometrical parameters and the surrounding dielectric environment refractive index (i.e., RI), gold nanoparticles have inner electromagnetic properties. Precisely speaking, the strongly enhanced localized surface plasmon resonance (LSPR) of this metal, at optical frequencies, allows them to be good light scatterers and absorbers (Kumar, Boruah & Liang, 2011). Additionally, gold nanoparticles promise to have good biocompatibility, optimal synthesis and conjugation properties (Patra, Bhattacharya, Mukhopadhyay, & Mukherjee, 2010) and are useful tools as contrast agents in cellular and biological imaging (Cho, Glaus, Chen, Welch, & Xia, 2010).

In terms of scattering and absorption cross-section, following assumptions need to be established for explaining the electromagnetic properties of the nanoparticle:

- The particle size should be much smaller than the wavelength in the surrounding medium. In this case, under the limit of electrically small particles, the electromagnetic field is almost unchanged over the particle volume, and then the resonant behavior of the structure can be studied in terms of a quasi-static approximation.
- The considered particle should be considered homogeneous and isotropic. In addition, the surrounding material is also a homogeneous, isotropic and non-absorbing medium.

3.9 Energy and Power

A nanomachine is composed of a power supply, memory, antenna and CPU module, and it behaves like an autonomous node capable of performing simple tasks such as computing, storing, sensing and/or actuating at the nano level (Afsana, Asif-Ur-Rahman, Ahmed, Mahmud, & Kaiser, 2018). A major challenge of nanosensor device is its energy storage capacity (Jornet & Akyildiz, 2012). However, energy harvesting is one of the possible solutions of this specific problem (Cottone, Vocca, & Gammaitoni, 2009; Gammaitoni, Neri, & Vocca, 2009; Wang, 2008; Xu, Hansen, & Wang, 2010a; Xu et al., 2010b). Piezoelectric nanogenerator is experimentally demonstrated in (Xu et al., 2010a). If the energy harvesting and the energy consumption processes are jointly designed, then the lifetime of energy-harvesting networks can considerably be increased (Gorlatova, Wallwater, & Zussman, 2013; Gummeson, Clark, Fu, & Ganesan, 2010). In classical battery-powered devices, the energy decreases until the battery is empty. But self-powered devices have both positive and negative fluctuations (Jornet & Aky-ildiz, 2012). The energy-harvesting process is perceived by means of a piezoelectric nanogenerator, for which a new circuital model is designed that can accurately reproduce existing experimental data. The energy consumption process is due to

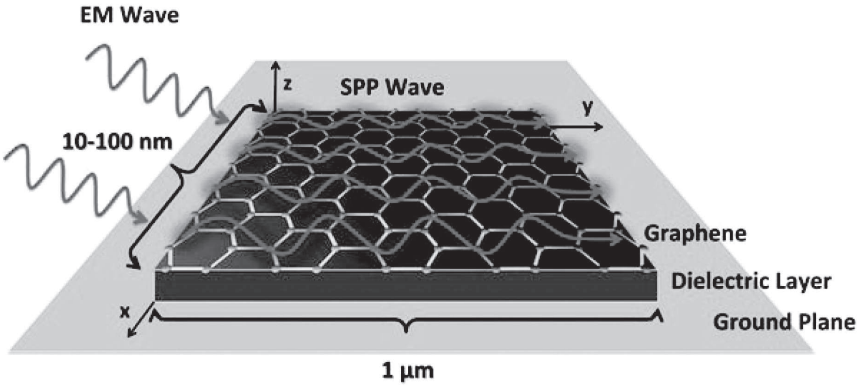

FIGURE 3.2 A graphene-based plasmonic antenna for THz Band communication. (Jornet & Akyildiz, 2013).

the communication among nanosensor motes in the terahertz band (Jornet & Akyildiz, 2012). It is judicious to consider that if a nanomachine fully deplenishes its battery and is unable to respond to a communication request, the transmitting nanomachine will attempt to retransmit. This would definitely increase the overall network traffic and multiuser interference, and it ultimately has an impact in the energy of the transmitting nanosensor mote and the neighboring nanomachines (Jornet & Akyildiz, 2012). (Jornet & Akyildiz, 2012) propose an energy model for self-powered nanosensor motes. The model considers both the energy harvesting process by means of a piezoelectric nanogenerator and the energy consumption process due to electromagnetic communication in the terahertz band (0.1–10.0 THz) (Jornet & Akyildiz, 2010a, 2011a,b). The model allows to compute the probability distribution of the nanosensor mote energy and to investigate its variations as function of several system and network parameters.

3.10 Nano-antenna

The way in which the nanomachines can communicate depends heavily on the way they are perceived (Akyildiz et al., 2011). Communication options for nanonetworks are very limited due to the size and ability of nanomachines. Graphene is considered as the marvel material of the 21st century. It is a one-atom-thick planar sheet that consists of carbon atoms arranged on a honeycomb crystal lattice. Two derivatives of graphene are CNTs: a folded nanoribbon, and GNR: a thin strip of graphene. Electromagntic nanocommunication is impossible in common frequency range, which is from hundreds of megahertz to few gigahertz. Because, in this range, the size of the antenna will be a few centimeters. If the size of antenna is reduced to a few hundred nanometers, it should operate in extremely high frequency i.e., in terahertz band. This, again, introduces many problems in electromagnetic communication such as high attenuation. However, nano-antenna, built from graphene, can overcome this limitation. For example, an antenna of few hundred nanometers would lean on the use of very high operating frequencies, which limits the communication range of nanomachines (Yao et al., 2015). Terahertz band, which spans the electromagnetic spectrum from 0.1THz to 10.0 THz (Llatser et al., 2012), is one of the least explored communication frequency ranges in electromagnetic spectrum (Jornet et al., 2012). Graphene and its derivatives (Martí et al., 2011), such as CNT (Jornet & Akyildiz, 2010b) and GNRs (Abadal et al., 2011), can be used to radiate at terahertz band. So the terahertz band (0.1–10.0 THz) is recommended as the transmission frequency band of nanonetworks. Figure 3.2 shows how graphene can be used to build novel plasmonic nano-antennas. As depicted in Figure 3.3, by using planar nano-antennas to create ultra-high speed links, the terahertz band can provide efficient and scalable means of inter-core communication in wireless on-chip networks. Figure 3.4 refers to a graphene-based nano-patch antenna which analyzes the performance in transmission and reception in terahertz band. The resonance frequency of the nano-antenna is calculated as a function of its length and width. The influence of a dielectric substrate with a variable size and the position of the patch with respect to the substrate have also been evaluated. They found that the radiation pattern of a graphene-based nano-patch antenna is very similar to that of an equivalent metallic antenna.

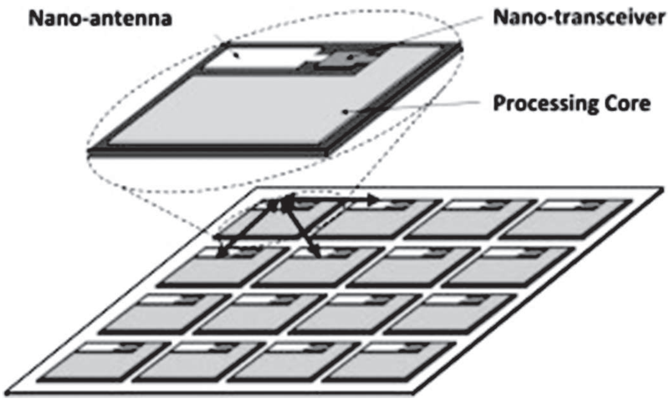

FIGURE 3.3 Wireless on-chip communication. (Abadal et al., 2013).

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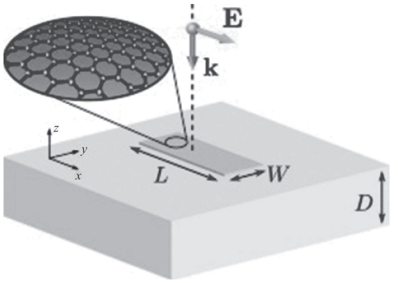

FIGURE 3.4 Schematic diagram of a graphene-based nanopatch antenna. (Llatser et al., 2012).

3.11 Routing Protocol for Terahertz Band Communication

Routing protocol for WNSN is remained in its infancy. The existing communication protocols may not be able to drive the nodes to communicate among themselves at the nanoscale. Therefore, these traditional protocols receive extensive revisions. Based on the transmission medium, different communication protocols have been proposed in course of time, which include acoustic, nanomechanical, molecular and electromagnetic (Akyildiz et al., 2014). A routing framework was introduced based on the peculiarities of the WNSNs, both in terms of terahertz band communication and nanoscale energy harvesting (Pierobon, Jornet, Akkari, Almasri, & Akyildiz, 2014). To reduce the complexity of network operation, a hierarchical cluster-based architecture was considered. This routing framework is based on a hierarchical cluster-based architecture where the WNSN is partitioned into clusters. Within each cluster, a nano-controller, which is a nanodevice with more advanced capabilities than a nanosensor, coordinates the nanosensors and gathers the data they communicate (Akyildiz & Jornet, 2010). An NS-3 module, namely Nano-Sim, modeling WNSNs based on electromagnetic communications in the terahertz band was presented in (Piro, Grieco, Boggia, & Camarda, 2013a). In this preliminary version, the Nano-Sim provides a simple network architecture and a protocol suite for such an emerging technology. In that very year, they have extended the tool by developing a new routing algorithm and a more efficient MAC protocol focusing on a WNSN operating in a health monitoring scenario (Piro, Grieco, Boggia, & Camarda, 2013b). A hierarchical network architecture integrating Body Area Nano-NETwork (BANNET) and an external macroscale healthcare monitoring system was introduced in (Piro, Boggia, & Grieco, 2015). Two different energy-harvesting aware protocol stacks using optimal routing protocol and a greedy routing approach have been formed for dealing with the communication of nanosensors moving uniformly in an environment mimicking human blood vessels. An energy-aware MAC protocol was applied in both strategies to identify the available nanonodes through a handshake mechanism. These two schemes performed well compared with the simple flooding scheme. However, high computational capacity was required for the optimal scheme. As a solution to the terahertz frequency-selective feature of networking, a channel aware forwarding scheme for EM-based WNSN in the terahertz band was proposed in (Yu, Ng, & Seah, 2015). The authors evaluated classical multihop forwarding and single end-to-end transmission schemes for EM-WNSNs. A Physical Layer Aware MAC protocol for EM nanonetworks in the THz band (PHLAME) has been proposed in (Jornet et al., 2012) where the transmitting and receiving nanomachines were allowed to jointly select the communication parameters in an adaptive fashion. The protocol was found to minimize interference in the nanonetwork and to maximize the probability of successfully decoding the received information. The energy and spectrum-aware MAC protocol was an approach to achieve incessant WNSNs (Wang, Jornet, Malik, Akkari, & Akyildiz, 2013). The objective was to achieve an ample throughput and lifetime optimal channel access by jointly optimizing energy-harvesting and energy-consumption processes in nanosensors. A method was to maximally utilize the harvested energy for nanonodes in perpetual WNSNs that communicate in the terahertz band (Mohrehkesh & Weigle, 2014). They developed an energy model as a Markov decision process considering that energy arrivals follow a stochastic process.

3.12 Sensing and Receiving

Nanomachiness (Akyildiz & Jornet, 2010), equipped with nanosensors, nanoactuator, nano-memory, nano-antenna, nano-EM transceiver, nano-processor and nano-power unit, will be able to exchange information through electromagnetic nanocommunications. In view of communication, the nanomachines will be able to accomplish more complex missions in a cooperative manner. As an example, nanosensors will be able to transmit the sensed information in a multi-hop fashion to a sink or a command centre. For electromagnetic nanonetworks, the exploitation of modulation and channel sharing mechanism based on the asynchronous exchange of femtosecond-long pulses, which are transmitted following an on-off keying modulation spread in time, has been proposed (Jornet & Akyildiz, 2011c). A receiver architecture for electromagnetic nanonetworks has been proposed in (Atakan & Akan, 2008) that makes use of pulse-based modulation. The receiver is designed to be very simple and robust, and it is based on a continuous-time moving average (CTMA) symbol detection scheme. This scheme bases its decision in the received signal power maximum peak after the CTMA, which is implemented with a single low-pass filter. Afterwards, to decode the symbol, this maximum is compared with a previously defined threshold.

3.13 Conclusion

In this chapter, we have addressed recent advances in electromagnetic nanocommunications. Starting from the description of possible applications and challenges, we have presented the state of the art of electromagnetic nanonetworks. We have found that terahertz is the only operating frequency for nanonetwork channel. Terahertz band communication and routing protocols are also addressed. It is found in the literature that an extensive study is required for transmission and routing protocol for terahertz band EM communication. We discuss about graphene-based nano-antenna, the most suited for terahertz communication. Energy harvesting models are also explored.

It can be inferred that nanomaterials are potential candidates for the design of innovative nanomachines. For instance, graphene-based nano-antennas can provide outstanding sensing capabilities, as well as graphene-based transistors are not only smaller but predictably faster too.

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