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Nanonetworks

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Synonyms

Nano communication networks

Definition

A nanonetwork is a set of interconnected nanomachines, i.e., devices that integrate nanometer-scale components, with computing, data storing, sensing, and actuation capabilities. Nanonetworks are expected to expand the capabilities of single nanomachines both in terms of complexity and range of operation by allowing them to coordinate, share, and fuse information. Nanonetworks enable new applications of nanotechnology in the biomedical field, environmental research, military technology, and industrial and consumer goods applications.

Historical Background

Nanotechnology and biotechnology are providing the engineering community with a new set of tools to control matter and program functions at the atomic and molecular scale. At this scale, novel nanomaterials, structures, and systems show new properties that cannot be realized at the microscopic level. By leveraging such properties, devices with unprecedented applications can be developed. Among others, nanosensors and nanoactuators, able to both monitor and control physical, chemical, and biological processes at the nanoscale, have been realized (Wu and Qu 2015).

The realization of nanomachines with computation, data storage, and communication, in addition to sensing and actuation capabilities, is enabling transformative applications of nanotechnology in diverse fields (Akyildiz et al. 2008). By means of communication, nanomachines will be able to complete more complex tasks in a distributed manner. In addition, the integration of resulting nanonetworks with macronetworks and eventually the Internet leads to the ultimate cyberphysical systems, known as the Internet of Nano Things (Akyildiz and Jornet 2010) and the Internet of Bio-Nano Things (Akyildiz et al. 2015).

X.(S.) Shen et al. (eds.), *Encyclopedia of Wireless Networks*,
https://doi.org/10.1007/978-3-319-32903-1_215-1

There are three paths toward developing nanomachines and enabling the communication between them, namely, *nanomaterial-based nanoscale electromagnetic networks*, *biomolecular communication networks*, and *hybrid nanonetworks*. Next, the state of the art is reviewed, and open challenges are identified for each approach.

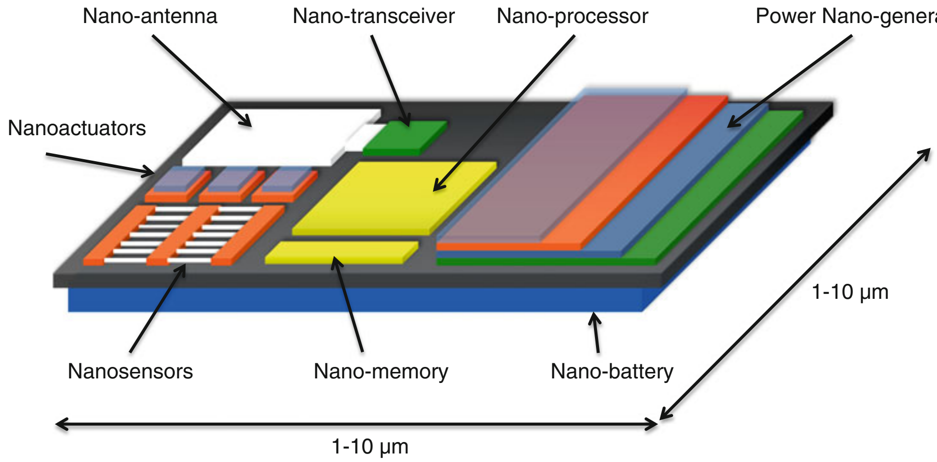
Nanomaterial-Based Nanoscale Electromagnetic Networks

From Nanomaterials to Nanomachines

Nanomaterials are materials with any external dimension in the nanoscale (sizes range from approximately 1–100 nm) or having internal structure or surface structure in the nanoscale. Among others, graphene (Ferrari et al. 2015), a one-atom-thick planar sheet of bonded carbon atoms in a honeycomb crystal lattice, has been and still is one of the most popular nanomaterials.Graphene exhibits very unique mechanical, electrical, and optical properties. Among others, it is the world's thinnest and lightest material while being harder than diamond; it is a very good conductor with very high electron mobility; and, despite being one atom thick, it can absorb light efficiently. Graphene is the first of a kind, but not the only two-dimensional material. As of today, more than 100 2D nanomaterials have reported, including molybdenum disulfide (MoS_2) (Splendiani et al. 2010) or hexagonal boron nitride (hBN) (Giovannetti et al. 2007), with different electronic properties. Moreover, the combination of different nanomaterials can lead to new nanostructures with novel properties (Geim and Grigorieva 2013).

By utilizing nanomaterials and the tools provided by nanotechnology, the different components which integrate a nanomachine (Fig. 1) can be realized, specifically,

- **Nano-processor** This is enabled by the development of smaller transistors. While 22 and 14 nm channel length transistor technologies are already commercial, the smallest transistor to date is based on a thin graphene strip made of just 10 by 1 carbon atoms, i.e., less than 1 nm long (Ponomarenko et al. 2008).
- **Nano-memory** Single-atom memories are at the basis of ultracompact data storing in nanomachines. For the time being, different single-atom memories based on different physical principles have been demonstrated, including electronic memories (Pla et al. 2012) and optical memories (Specht et al. 2011).
- **Power Nano-generator** In addition to nano-batteries (Brazier et al. 2008), energy-harvesting nano-systems or power nano-generators are needed for nanomachines to be able to continuously operate. Different energy-harvesting systems have been demonstrated to date, including mechanical energy harvesting through devices (Wang et al. 2017) or EM energy harvesting (Gadalla et al. 2014).
- **Nanosensor and Nanoactuator** Physical, chemical, and biological nanosensors and nanoactuators have been developed by using graphene and other nanomaterials. These are able to detect and measure magnitudes at the nanoscale, including the physical characteristics of structures just a few nanometers in size or the presence of biological agents such as virus or cancerous cells (Wu and Qu 2015).
- **Nano-transceiver and Nano-antenna** Nanomachines require miniature transceivers and antennas to communicate. On the one hand, noble metals can be utilized to fabricate plasmonic nano-antennas, which are just hundreds of nanometers in length and can efficiently operate at infrared and visible optical frequencies (Nafari and Jornet 2017). These require similarly small nano-lasers (Feng et al. 2014) and nano-photodetectors (Luo et al. 2016) to operate. On the other hand, graphene can be utilized to fabricate miniature nano-transceivers (Jornet and Akyildiz 2014b) and nano-antennas (Jornet and Akyildiz 2013), which can efficiently operate in the terahertz (THz) band (0.1–10 THz), i.e., at a frequency much lower than their metallic



Nanonetworks, Fig. 1 Conceptual architecture of a nanomachine

counterparts. These bring many opportunities for communication in nanonetworks, as it is explained next.

Besides the fabrication of each one of the components, there are several challenges related to their integration in a single device. While self-assembly techniques, including DNA scaffolding (Maune et al. 2010), are being developed, the utilization of a single nanomaterial or arrangement of nanomaterials to fabricate the different components at once will drastically simplify the realization of nanomachines.

Terahertz and Optical Nanoscale Communication

The very small size of nano-antennas imposes the use of very high frequencies for EM wireless communication among nanomachines, ranging from the THz band to the infrared and visible optical frequency bands. This introduces multiple challenges and opportunities for communication and networking:

- **Channel Modeling** There are three main phenomena which affect the propagation of EM waves at THz band and optical frequencies, namely, spreading, absorption, and scattering. Common to any wireless communication system, the *spreading loss* refers to attenuation due to the expansion of the wave front as it propagates through the medium. The *scattering loss* refers to the signal loss due to redirection (reflection, diffusion) of EM waves as they propagate through a medium with obstacles, which depends on the obstacle size in terms of wavelength. At THz frequencies, the main problem is posed by molecular absorption (Jornet and Akyildiz 2011; Han et al. 2015), whereas at optical frequencies, scattering is the main challenge to overcome (Johari and Jornet 2018). In both cases, the channel can support beyond multi-GHz transmission bandwidths.
- **Physical Layer** The capabilities of nanomachines and the peculiarities of the channel need to be taken into account when designing the physical layer. In terms of *modulation*, the transmission of 100-femtosecond-long pulses spread in time has been proposed as a way to enable ultra-broadband communication in nanonetworks (Jornet and Akyildiz 2014a). These pulses have their main frequency components in the THz band (between 0.5 and 4 THz), can be generated with nano-transceivers, and are already widely used in THz sensing applications. Similarly, new *channel coding* strategies are needed to overcome channel errors resulting from weak signals, noise, and multiuser interference, such as low-weight channel codes (Jornet 2014).

Independently of the modulation and coding strategy, physical-layer synchronization is a major bottleneck to overcome, due to the very low power and very short duration of the symbols.

- **Link Layer and Above** The very large available bandwidth at THz and optical frequencies reduces the need for the nodes to contend for the channel. However, the energy fluctuations, due to the use of energy-harvesting systems, require the development of link-layer synchronization and *medium access control (MAC)* algorithms for both ad hoc and infrastructure nanonetworks (Wang et al. 2013). Moreover, the very large number of nanomachines in nanonetworks requires the development of new *addressing* schemes, beyond IPv6, which leverage the hierarchical nature of nanonetworks and built upon compressed-addressing concepts. In addition, due to the limited transmission range of nanomachines, *multi-hop relaying and routing* strategies need to be developed (Pierobon et al. 2014; Tsioliaridou et al. 2015). Ultimately, ensuring *end-to-end reliability* will require the revision of well-established concepts at the transport layer.

Biomolecular Communication Networks

Bio-nanomachines

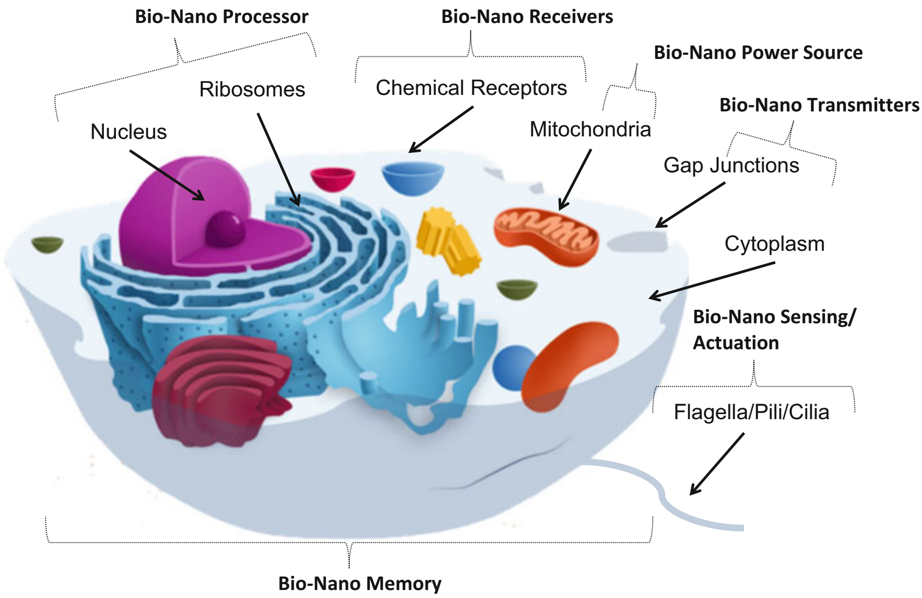
Bio-nanomachines are uniquely identifiable basic structural and functional units that operate and interact within the biological environment. Stemming from biological cells, the basic units of life, and enabled by synthetic biology and nanotechnology, they are based on the control of biological processes (Akyildiz et al. 2015). Biotechnology, through DNA sequencing and synthesis tools, is enabling the reading and writing of cells' genetic code (Kahl and Endy 2013), providing open access to the set of structural and functional instructions at the basis of life. At the same time, nanotechnology is expanding these directions toward the assembly of artificial cells (Wu and Tan 2014).

The different components of a bio-nanomachine can be abstracted from the main components of a biological cell (Fig. 2) as follows:

- **Bio-Nano Processor** This corresponds to the molecular machinery that, from the DNA molecules (contained in the nucleus) to the so-called transcription and translation (at the ribosomes), generates protein molecules with instruction-dependent types and concentrations.
- **Bio-Nano Memory** This is an abstraction of the chemical content of the cytoplasm, i.e., the interior of the cell, comprised of molecules synthesized by the cell as a result of DNA instructions, and other molecules or structures, e.g., vesicles, exchanged with the external environment, and organelles, including the nucleus in case of eukaryotic cell, as shown in Fig. 2.
- **Bio-Nano Power Source** This is the reservoir of adenosine triphosphate (ATP) molecule, which is synthesized by the cell from energy supplied from the external environment in various forms, and provides the chemical energy necessary for the cell biochemical reactions to take place. In the case of eukaryotic cells, ATP production occurs in mitochondria.
- **Bio-Nano Sensing and Actuation** This corresponds to the capability of a cell to chemically recognize external molecules or physical stimuli, e.g., light or mechanical stress, and to change the chemical characteristics of the environment or mechanically interact through moving elements, such as flagella, pili, or cilia.
- **Bio-Nano Transceivers** These are abstractions of specific chains of chemical reactions, i.e., signaling pathways, through which cells exchange information with each other and the environment.

Biomolecular Communications

Individual biological cells and cell populations perceive, elaborate, and exchange information through the propagation of molecules and their chemical reactions (Payne and You 2014), which



Nanonetworks, Fig. 2 Main components of a eukaryotic cell (with nucleus) and their abstraction as components of a bio-nanomachine

can be abstracted according to the paradigm of molecular communication (MC) (Akyildiz et al. 2011). The heterogeneity of biological MC mechanisms and the fundamental differences with respect to classical communication scenarios pose the following unique challenges and opportunities for the realization of bio-nanomachine interconnections into MC networks:

- **Channel Modeling** Several different MC mechanisms can be observed in nature that do not behave as the channels previously considered when engineering communication systems. In particular, the peculiarities of channels based on the simplest mechanism of molecular diffusion in terms of path loss and signal distortion (Pierobon and Akyildiz 2010), and their associated noise sources (Pierobon and Akyildiz 2011; Noel et al. 2014), necessitated completely novel interference (Pierobon and Akyildiz 2011), channel estimation (Jamali et al. 2016), and channel capacity (Pierobon and Akyildiz 2013; Atakan and Akan 2010) analyses. Other simple MC mechanisms have been considered, such as molecular motors (Moore et al. 2006), gap junctions (Nakano et al. 2007; Kilinc and Akan 2012; Barros et al. 2015), and chemotaxis (Gregori and Akyildiz 2010), along with more complex MC scenarios, such as the cardiovascular system (Chahibi et al. 2013), while more fundamental communication theoretical aspects related to molecular information have been treated in Akan et al. (2017).
- **Physical Layer** The design of physical links between bio-nanomachines has to take into account different options to realize information encoding and modulation in MC systems, along with their theoretical performance (Lu et al. 2015; Murin et al. 2017), and molecular mechanisms to optimize signal detection and decoding (Kilinc and Akan 2013; Mahfuz et al. 2014, 2015; Chou 2015; Li et al. 2016; Jamali et al. 2018). Ultimately, the peculiarities of the underlying biological cells and the tools for their engineering should be accounted for. In this direction, synthetic-biology-enabled analog communications have been studied in Pierobon (2014) while digital-like communications in Unluturk et al. (2015). Channel coding strategies adapted to the effi-

ciency of analog processing in cells have been suggested in Marcone et al. (2017).

- **Link Layer and Above** The definition of network architectures and protocols on top of the aforementioned biological MC systems will be particularly challenging given the nonlinear nature of many biochemical phenomena (Mian and Rose 2011) and the shared nature of the media, such as fluids (Deng et al. 2017). Optimization in terms of energy consumption for information propagation within these networks will be also an important aspect (Qiu et al. 2017), since cells have limited resources. A further challenge will be the interconnection of heterogeneous networks, i.e., composed of different types of bio-nanomachines and/or based on different biological MC mechanisms. The realization of interfaces between the electrical domain and the biochemical domain will be the ultimate frontier to create a seamless interconnection between the biological environment and the Internet.

Hybrid Nanonetworks

Beyond nanomaterial-based nanomachines or synthetically engineered living cells, hybrid nano-bio-engineered nanomachines and nanonetworks will exhibit unique capabilities and enable applications, even yet to be envisioned. Among others, *optogenetics*, i.e., the use of light to control and monitor genetically engineered living cells, is at the basis of fundamental studies in developmental and neurodegenerative diseases as well as of brain machine interfaces, which can restore and even enhance functional abilities and cognition (Wirdatmadja et al. 2017). Beyond optogenetics, optogenomics, i.e., the control of gene expression with light, can lead to unprecedented control of biological processes. For all these, hybrid nanomachines, able to manipulate and interact with electromagnetic (THz, optical) and molecular signals, need to be developed.

Key Applications

The potential applications of the nanonetworks can be classified in four main areas: *biomedical applications*, including intrabody health monitoring and drug delivery systems, immune system support mechanisms, and artificial biohybrid implants; *industrial and consumer goods applications*, development of intelligent functionalized materials and fabrics, new manufacturing processes and distributed quality control procedures, and food and water quality control systems; *environmental applications*, biological and chemical nanosensor networks for pollution control, biodegradation assistance, and animal and biodiversity control; and *military applications*, nuclear, biological, and chemical defenses and nano-functionalized equipment and human enhancement.

Cross-References

► Brain Machine Interfaces
► Nanoscale Terahertz Communications

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