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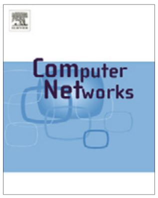

Nanonetworks: A new communication paradigm

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ABSTRACT

Nanotechnologies promise new solutions for several applications in biomedical, industrial and military fields. At nano-scale, a nano-machine can be considered as the most basic functional unit. Nano-machines are tiny components consisting of an arranged set of molecules, which are able to perform very simple tasks. Nanonetworks. i.e., the interconnection of nano-machines are expected to expand the capabilities of single nano-machines by allowing them to cooperate and share information. Traditional communication technologies are not suitable for nanonetworks mainly due to the size and power consumption of transceivers, receivers and other components. The use of molecules, instead of electromagnetic or acoustic waves, to encode and transmit the information represents a new communication paradigm that demands novel solutions such as molecular transceivers, channel models or protocols for nanonetworks. In this paper, first the state-of-the-art in nano-machines, including architectural aspects, expected features of future nano-machines, and current developments are presented for a better understanding of nanonetwork scenarios. Moreover, nanonetworks features and components are explained and compared with traditional communication networks. Also some interesting and important applications for nanonetworks are highlighted to motivate the communication needs between the nano-machines. Furthermore, nanonetworks for short-range communication based on calcium signaling and molecular motors as well as for long-range communication based on pheromones are explained in detail. Finally, open research challenges, such as the development of network components, molecular communication theory, and the development of new architectures and protocols, are presented which need to be solved in order to pave the way for the development and deployment of nanonetworks within the next couple of decades.

1. Introduction

The concepts in nanotechnology was first pointed out by the 1965 nobel laureate physicist Richard Feynman in his famous speech entitled "*There's Plenty of Room at the Bottom*" in December 1959. The main focus of his speech was about the field of miniaturization and how he believed humans would create increasingly tinier and powerful devices in the future. The term "nanotechnology" was first defined by [59] 15 years later as: "Nanotechnology mainly consists of the processing of, separation, consolidation, and deformation of materials by one atom or by one molecule". In the 1980s, the basic idea of this definition was explored in much more depth by [26] who took the Feynman concept of a billion tiny factories and added the idea that they could replicate themselves, via computer control instead of control by a human operator. Activity surrounding nanotechnology began to slowly increase and the advancements really began to accelerate in the early 2000s.

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Nanotechnology enables the miniaturization and fabrication of devices in a scale ranging from 1 to 100 nanometers. At this scale, a nano-machine can be considered as the most basic functional unit. Nano-machines are tiny components consisting of an arranged set of molecules which are able to perform very simple computation, sensing and/or actuation tasks [57]. Nano-machines can be further used as building blocks for the development of more complex systems such as nano-robots and computing devices such as nano-processors, nano-memory or nano-clocks.

Nano-machines can be interconnected to execute collaborative tasks in a distributed manner. Resulting nanonetworks are envisaged to expand the capabilities and applications of single nano-machines in the following ways:

- Nano-machines such as chemical sensors, nano-valves, nano-switches, or molecular elevators [4], cannot execute complex tasks by themselves. The exchange of information and commands between networked nano-machines will allow them to work in a cooperative and synchronous manner to perform more complex tasks such as in-body drug delivery or disease treatments.
- The workspace of a single nano-machine is extremely limited. Nanonetworks will allow dense deployments of interconnected nano-machines. Thus, larger application scenarios will be enabled, such as monitoring and control of chemical agents in ambient air.
- In some application scenarios, nano-machines will be deployed over large areas, ranging from meters to kilometers. In these scenarios, the control of a specific nano-machine is extremely difficult due to its small size. Nanonetworks will enable the interaction with remote nano-machines by means of broadcasting and multihop communication mechanisms.

Communication between nano-machines can be realized through *nanomechanical, acoustic, electromagnetic and chemical or molecular communication* means [31].

Nanomechanical communication is defined as the transmission of information through mechanical contact between the transmitter and the receiver. In *acoustic communication*, the transmitted message is encoded using acoustic energy, i.e., pressure variations. *Electromagnetic communication* is based on the modulation of electromagnetic waves to transmit information. *Molecular communication* can be formally defined as the use of molecules as messages between transmitters and receivers.

Molecular communication is the most promising approach for nano-networking based on the following advantages:

- Due to the size and principles of traditional acoustic transducers and radiofrequency transceivers, their integration at molecular or nano-scale is not feasible [31]. By contrast, molecular transceivers are intrinsically conceived at nano-scale. These are nano-machines which are able to emit and receive molecules.
- In nanomechanical communication, transmitters and receivers need to be in direct contact. This is not a restriction for molecular communication over large areas, where transmitters and receivers can be remotely located as long as the transmitted molecules reach the intended receiver.

In the recent literature, the term "nanonetworks" refers to electronic components and their interconnection within a single chip on a nano-scale [12]. This concept is also known as Network on Chip (NoC). This term is also referred to as the network-like interconnection of nanomaterials as well, e.g., carbon nanotubes arrays [38,15]. In this paper, we use the term "nanonetworks" strictly for the interconnection of nano-machines based on molecular communication.

This paper follows the bio-inspired approach to explore, from a telecommunication point of view, the potential of molecular communication for nanonetworks. First, in Section 2, we present the nano-machines including the state-of-the-art in research and current approaches for their development. In Section 4, we explain nanonetwork features and their advantages and disadvantages over traditional communication networks. In Section 3, we explain potential applications of nanonetworks. We explore existing biological models and techniques for molecular communication for short and long-ranges in Sections 5–7, respectively. Finally, we outline open research issues and contrast them with traditional communication network challenges in Section 8. We conclude the paper in Section 9.

2. Overview of Nano-machines

A nano-machine is defined as "*an artificial eutactic mechanical device that relies on nanometer-scale components*" [24]. Also the term "*molecular machine*" is defined as "*a mechanical device that performs a useful function using components of nanometer-scale and defined molecular structure; includes both artificial nano-machines and naturally occurring devices found in biological systems*".

In general terms, we define a nano-machine as "*a device, consisting of nano-scale components, able to perform a specific task at nano-level, such as communicating, computing, data storing, sensing and/or actuation*". The tasks performed by one nano-machine are very simple and restricted to its close environment due to its low complexity and small size.

There are three different approaches for the development of nano-machines as depicted in Fig. 1. In the *top-down approach*, nano-machines are developed by means of downscaling current microelectronic and micro-electro-mechanical technologies without atomic level control. In the *bottom-up approach*, the design of nano-machines is realized from molecular components, which assemble themselves chemically by principles of molecular recognition arranging molecule by molecule. Recently, a third approach called *bio-hybrid* is proposed for the development of nano-machines [63]. This approach is based on the use of existing biological nano-machines, such as molecular motors, as components or models for the development of new nano-machines. In Fig. 1, different systems are mapped according to their origin, biological or man-made