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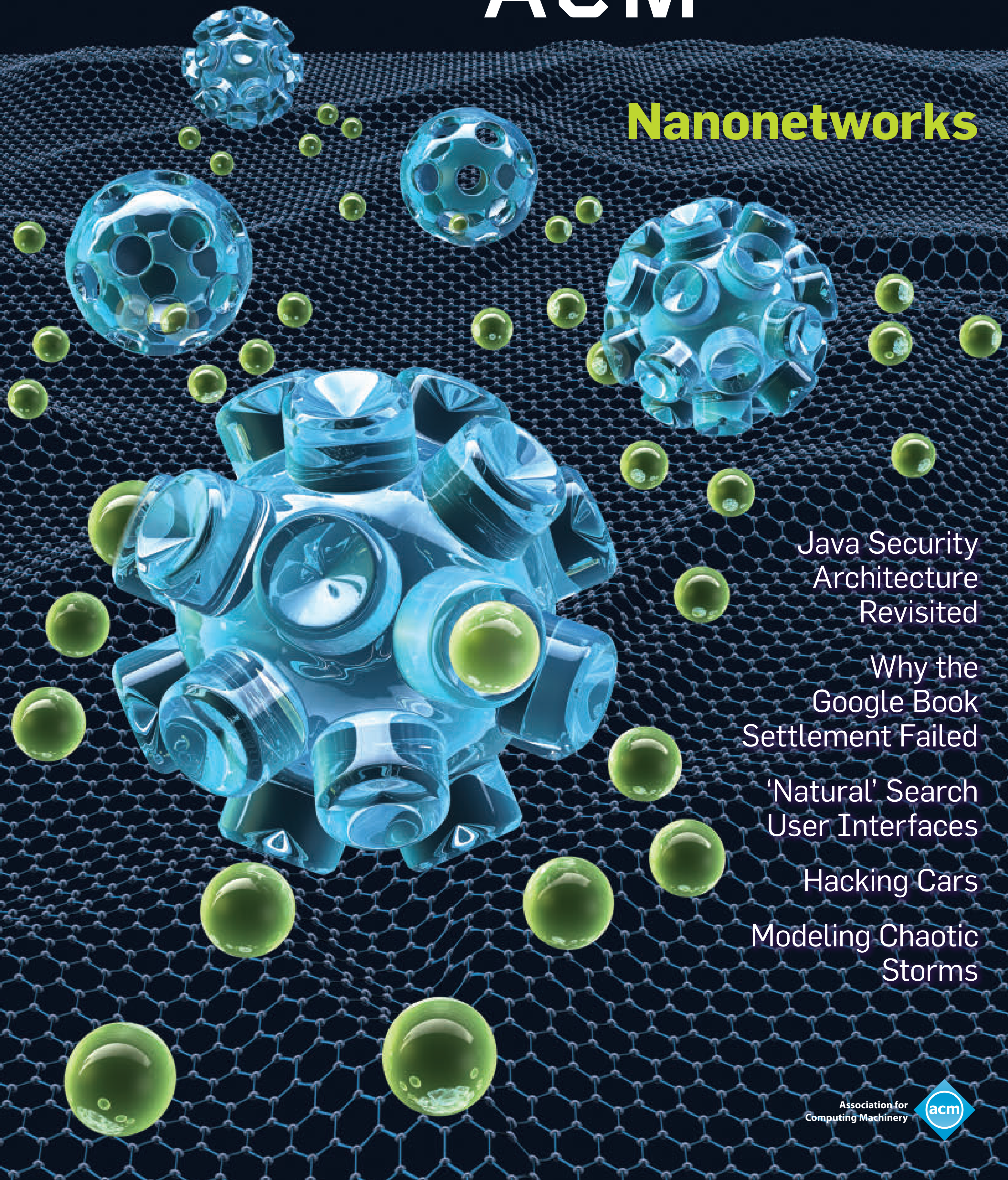

Nanonetworks

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Technology able to create devices the size of a human cell calls for new protocols.

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Nanonetworks: A New Frontier in Communications

IN 1959, THE Nobel laureate physicist Richard Feynman, in his famous speech entitled "There's Plenty of Room at the Bottom," described for the first time how the manipulation of individual atoms and molecules would give rise to more functional and powerful man-made devices. In his vision, he talked about having a billion tiny factories able to manufacture fully functional atomically precise nano-devices. During the same talk, he noted that several scaling issues would arise when reaching the nanoscale, which would require the engineering community to totally rethink the way in which nano-devices and nano-components are conceived.

More than a half-century later, current technological trends, which are still mainly based on the miniaturization of existing manufacturing techniques, are facing these predicted limitations. Consequently, there is a need to rethink and redesign the way in which components and devices are created by taking into account the new properties of the nanoscale. Moreover, a whole new range of applications can be enabled by the development of devices able to benefit from these nanoscale phenomena from the very beginning. These are the tasks at the core of the nanotechnology.

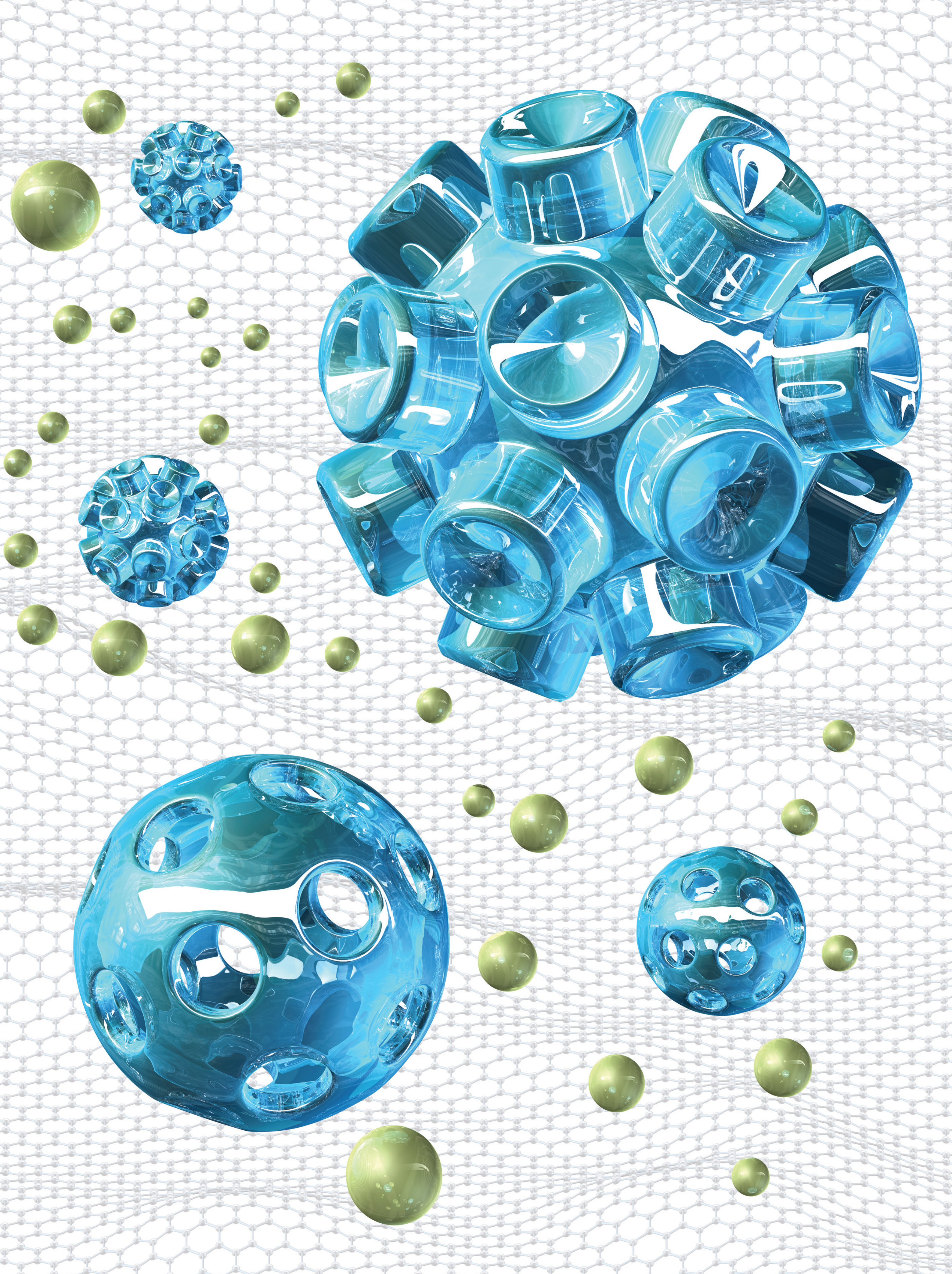
The term *nanotechnology* was first defined in a work dated from 1974[15] as follows: *"Nanotechnology mainly consists of the processing of, separation, consolidation, and deformation of materials by one atom or by one molecule."* Later, in the 1980s, the basic concept of this definition was explored in much more depth by K. Eric Drexler,[3] who took Feynman's vision about creating nano-devices by using tiny factories, and added the idea that they could replicate themselves via computer control instead. For more than 10 years, Drexler received numerous accusations of promoting science fiction. However, as the first simple structures on a molecular scale were obtained, the activities surrounding nanotechnology began to slowly increase and this term became more socially accepted. It was in the early 2000s when the major advancements in the field ramped up.

Among the different aims of nanotechnology, we focus on the development of *nanomachines*, that is, integrated functional devices consisting

» key insights

- **Nanotechnology is providing a new set of tools to the engineering community to design and manufacture nanomachines; that is, basic functional nano-devices able to perform only very simple tasks.**
- **Nanonetworks—networks of nanomachines—will expand the capabilities of single nanomachines by providing them a way to cooperate and share information.**
- **It is still not clear how nanomachines will communicate. Two main alternatives currently being considered are Terahertz Band and molecular communications.**

ILLUSTRATION BY GIACOMO MARCHESI



of nanoscale components and which are able to perform simple tasks at the nano-level. Going one step ahead, we propose the interconnection of nanomachines in a network or *nanonetwork* as the way to overcome the limitations of individual nano-devices.[1,2] The potential applications of the resulting nanonetworks are almost unlimited and can be classified in four main areas: *Biomedical Applications* (for example, intrabody health monitoring and drug delivery systems, immune system support mechanisms, and artificial bio-hybrid implants); *Industrial and Consumer Goods Applications* (for example, development of intelligent functionalized materials and fabrics, new manufacturing processes and distributed quality control procedures, 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).

Several communication paradigms can be used in nanonetworks depending on the technology used to manufacture the nanomachines and the targeted application. In this article, we provide an overview of the two main alternatives for nanocommunication, that is, Electromagnetic Communications in the Terahertz Band and Molecular Communications. Our aim is to provide a better understanding of the current research issues in this truly interdisciplinary and emerging field, and to pave the way of future research in nanonetworks. We also review the state of the art in the design and manufacturing of nanomachines, discuss the different alternatives for communication in the nanoscale, and describe the research challenges in the design of protocols for nanonetworks. While there is still a long way to go before a fully functional nanomachine is realized, we believe hardware-oriented research and communication-focused investigations will benefit from being conducted in parallel from an early stage.

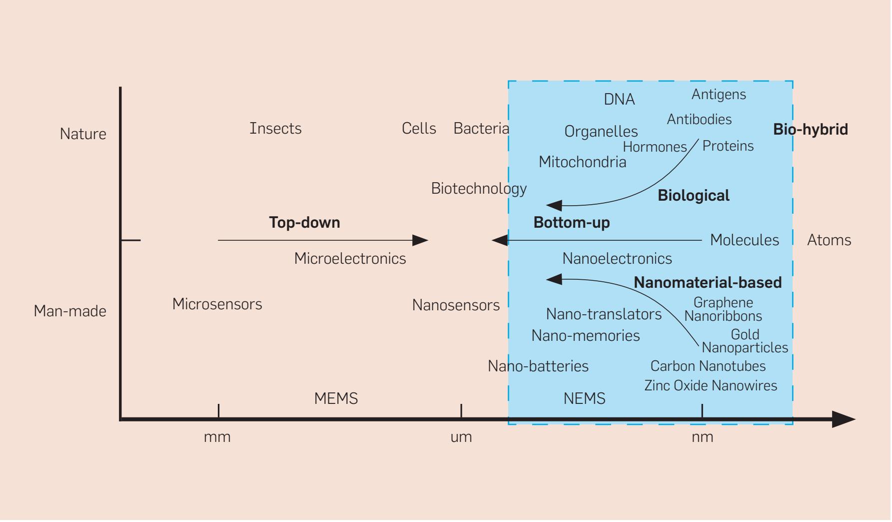
Manufacturing Nanomachines

Nanonetworks start at the interconnection of several nanomachines. The capabilities and the application range of these nanomachines strongly depend on the way in which they are manufactured. As shown in the accompanying figure, different approaches can be used for their development, ranging from the use of man-made components to the reuse of biological entities found in nature. These approaches are classified into three main branches, namely, top-down, bottom up and bio-hybrid.[1] In the *top-down* approach, nanomachines 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 the (self) assembly of molecular components and synthesized nanomaterials. Alternatively, in a *bio-hybrid* approach, existing biological components, such as Deoxyribonucleic Acid or DNA strands, antibodies or molecular motors, are combined with man-made nano-structures to develop new nanomachines.

Man-made machines. Despite several technological and physical limitations, the evolution of classical lithography techniques and other non-standard manufacturing procedures have been used to fabricate components with at least one of their dimensions in a scale below 100nm.[16] A special emphasis should be given to the study of nanomaterials and new manufacturing processes, which are enabling a new direction for the development of nano-components. As an example, field-effect transistors can be obtained through the use of graphene nanoribbons and carbon nanotubes, and these can be used as the building block for new computing machines.[14] Other well-studied nano-components are nanomaterials-based biological, chemical, and physical nanosensors and nanoactuators. The integration of several of these nano-components into a single functional unit will result in a device with a total size in between 10–100 square micrometers,[2] which is comparable to the size of an average human cell. However, the integration of these components into a single device is still one of the major challenges in the manufacturing of nanomachines.

Adopting components coming from nature. The nanoscale is the natural domain of molecules, proteins, DNA, organelles and the major components of cells. Some of these nano-components can be used as building blocks for integrated nano-devices. As an example, Adenosine TriPhosphate or ATP batteries emulating the behavior of *mitochondria*, often described as "cellular power plants," can be an alternative energy source for bio-nano-devices. In addition, information encoded in DNA can be used for molecular computing machines and molecular memories. Alternatively, DNA strands can also be used to build miniature circuit boards and to stimulate the self-assembly of components such as carbon nanotubes, nanowires, nanoribbons and

Approaches for the development of nanomachines.



nanoparticles, by means of DNA scaffolding.[9] While still being one step behind nanomaterial-based component manufacturing, we believe that being able to directly reuse biological structures found in living organisms or to reengineer them will be especially useful in biomedical applications, as well as the enabling technology for bio-inspired communications.

Enabling Communication Among Nanomachines

Nanocommunication is the exchange of information at the nanoscale and it is at the basis of any wired/wireless interconnection of nanomachines in a nanonetwork. The way in which the nanomachines can communicate depends strongly on the way they are realized. Moreover, the particular application for which the nanonetworks will be deployed constrains the choice on the particular type of nanocommunication. For the time being, several alternatives have been proposed. These range from downscaling well-established communication means based on electromagnetic, optical, acoustic, or mechanical communication, up to defining completely new paradigms inspired by biology.

Downscaling existing communication paradigms. The tools provided by nanotechnology are enabling the extension of well-known communication techniques to the nanoscale. First of all, carbon nanotubes and graphene nanoribbons have been proposed for electromagnetic nano-antennas.[6] A graphene-based nano-antenna is not just a mere reduction of a classical antenna, but there are several quantum phenomena that affect the propagation of electromagnetic waves on graphene. As a result, the resonant frequency of these nanostructures can be up to two orders of magnitude below that of their non-carbon-based counterparts. However, their radiation efficiency can also be impaired because of this phenomenon. Second, carbon nanotubes have also been proposed as the basis of an electromechanical nano-transceiver or nano-radio,[5] able to modulate and demodulate an electromagnetic wave by means of mechanical resonation. This technique has been experimentally proved in reception, but would require very high nanoscale power sources for active transmission.

Terahertz Band: Ultra-broadband communications in nanonetworks. Focusing on the use of graphene-based nano-antennas and thinking of the expected maximum size of a nanomachine, the Terahertz Band (0.1THz–10THz) enters the game. Indeed, we have recently shown that a one-micrometer-long graphene-based nano-antenna would expectedly resonate in the aforementioned band.[6] This very high-frequency range, in between the microwaves and the far-infrared radiation, has recently caught the attention of the scientific community because of its applications in security screening and nanoscale imaging systems. In our case, we think of the Terahertz Band as a very large transmission window that can support very high transmission rates in the short range, that is, up to a few Terabits per second for distances below one meter, or as several transmission windows more than 10 gigahertz-wide each as we've recently shown.[7] For the time being, it is not clear how nanomachines with limited capabilities can exploit the properties of this huge band, but several options come to mind. For example, we have recently proposed the use of very low energy femtosecond-long pulses as a simple but robust communication paradigm for nanomaterial-based nanomachines.[8] Moreover, having a very large available bandwidth introduces major changes in classical networking protocols, as we describe here.

Learning from biology: Molecular communication. Cells and many living organisms exchange information by means of molecular communication, that is, they use molecules to encode, transmit and receive information. Among others, one of the most widespread molecular communication mechanisms is based on the free diffusion of molecules in the space. For example, communication between neighboring cells in the human body is conducted by means of diffusion of different types of molecules, which encode different types of messages. To date, research has been carried out to study the propagation of molecular messages by means of free diffusion. Among others, in Pierobon and Akyildiz,[7] we analyzed the behavior of the molecular diffusion channel in terms of attenuation and delay. In the same paper, we provide mathematical models of the physical processes occurring at the molecular transmission, propagation and reception. The results of this work are in two different directions. First, they provide a numerical evaluation of the communication capabilities of the physical channel. Attenuation values of tens of dB for a transmission range up to 50 micrometers and a frequency up to 400Hz (but hundreds of dB when the frequency approaches 1kHz) have been obtained with a delay of more than 100ms. Second, the results define reliable and simple models, which can be used off the shelf in the design of molecular communication systems based on the free diffusion of molecules. We expanded our understanding of the molecular diffusion channel by analyzing the most relevant diffusion-based noise sources, whose origins are intrinsically different than for noise sources in EM communication.[13] Theoretical limits on the information capacity of a diffusion-based molecular communication system are studied in Pierobon and Akyildiz.[12] We show that the order of magnitude of the capacity for a molecular communication system is extremely higher than the capacity of classical communication systems. These results confirm the growing interest around molecular communication for nanonetworks shown by the research community in the last couple years.

Alternatively, in Parcerisa and Akyildiz,[10] we proposed the use of pheromones for molecular communication in long-range nanonetworks, such as, for transmission distances approximately one meter. Pheromones are molecules of chemical compounds released by plants, insects, and other animals that trigger specific behaviors among the receptor members of the same species and whose propagation relies also on the molecular diffusion process. In the same paper, we present other molecular communication techniques, such as neuron-based communication and capillaries flow circuits. The former refers to the possibility of building a communication system directly inspired by the nerve fibers that transport muscle movements, external sensorial stimuli, and neural communication signals to and from the brain. The latter are inspired by the capillaries, which are the smallest blood vessels inside the human body. Capillaries connect arterioles and venules and their main function is to interchange chemicals and nutrients between the blood and the surrounding tissues. The feasibility and practicality of these systems still needs to be investigated, but they can serve as a starting point for future bio-inspired nanocommunication systems.

Last but not least, we proposed and studied in Gregori and Akyildiz[4] a molecule transport technique using two different types of carrier entities, namely, flagellated bacteria and catalytic nanomotors. On the one hand, the flagellated bacteria are able to carry DNA messages introduced inside their cytoplasm. When set free in the environment, the carrier bacteria are headed to the receiver, which is continuously releasing bacteria attractant particles. Upon contact with the receiver, the bacteria release the DNA message to the destination. On the other hand, the catalytic nanomotors are defined as particles that are able to propel themselves and small objects. Nanomotors can be loaded with DNA molecules and their propagation can be guided using preestablished magnetic paths from the emitter to the receiver. Nanomotors can also compose a raft and transport the DNA message through a chemotactic process. The propagation of information by means of guided bacteria or catalytic nanomotors is relatively very slow (in the order of a few millimeters per hour), but the amount of information that can be transmitted in a single DNA strand makes the achievable information rate relatively high (up to several kilobits per second). All these results require us to rethink well-established concepts in communication and network theory.

While there is still a long way to go before a fully functional nanomachine is realized, we believe hardware-oriented research and communication-focused investigations will benefit from being conducted in parallel from an early stage.

Developing Nanonetworking Protocols

Nanonetworks are systems composed by interconnected nanomachines that communicate by following specific protocols. These protocols must address various issues not only common to conventional networks, but also arising from the peculiarities of the different nanocommunication options. For this, several features required in any communication network, such as Medium Access Control (MAC) mechanisms, addressing schemes, or information routing techniques, must be designed in light of the properties of the aforementioned nanocommunication paradigms

Terahertz nanonetworks. The Terahertz Band provides a very large transmission bandwidth. On the one hand, this can be used to support very high-speed communication among nano-devices. On the other hand, a very large bandwidth enables new channel access techniques, which can ease the tasks of the MAC protocol. For example, when using femtosecond-long pulses for communication among nano-devices,[2] the chances of having a collision between different nanomachines' transmissions are almost non-existent. As a result, very simple MAC protocols can be used. For instance, nanomachines can just transmit whenever they have some information ready and then they just wait for an acknowledgment. New ways to verify the integrity of the message that has been transmitted and to accordingly inform the transmitter will be necessary. In addition, in light of the capabilities of nanomachines, new coding schemes and error correction mechanisms will have to be developed. When it comes to addressing and routing, it will also be the capabilities of nanomachines what will determine what is possible and what is not. For example, it seems unfeasible to assign a unique ID to every component of a nanonetwork. Alternatively, by exploiting again the nature of pulse-based communications, we think that nanomachines will have a notion of the distances among them, which can be used for addressing and routing purposes. At the same time, in our vision, we believe that in some applications it will not be necessary to uniquely identify every nanomachine, but it will be enough by just classifying the nanomachines according to their internal status, for example, the sensing readings.

Molecular nanonetworks. Molecular nanonetworks require the development of new networking protocols suited for the nature of this new paradigm. In our vision, the study of the molecular network protocols will follow a twofold approach: on the one hand, network structures and protocols will be directly inspired from the observation of communication and signaling processes from nature (biologically inspired molecular networks); on the other hand, classical networking paradigms will be adapted for their use with synthesized molecular nanonetworks. In both of the two cases, these protocols will have to take into account the delay in the propagation of molecular information, which is considerably high if compared to electromagnetic communications. The study of a MAC protocol should also take into account the effects of the interaction of multiple molecular transmitters in the same environment. The performance of the molecular communication system in terms of attenuation and delay will likely vary due to the interactions physically occurring between molecules emitted by different transmitters, such as collisions or electrical and chemical reactions. Therefore, a MAC protocol will be required to minimize the interference between different emitters and to maximize the overall throughput of the network. Moreover, routing and addressing aspects will be required to enable communication between multiple source and destination points. In our vision, any form of addressing will be likely embedded within the structure of the molecules that compose the information message, such as their type or even electrical charge. Molecular protocols will also be studied in relation to the particular adopted molecular communication technique. As an example, when pheromones are used as information carriers, routing protocols will have to take into account the fact that their propagation in the air medium is highly dependent on the direction of the wind flow. Particular geographical routing algorithms could exploit the knowledge of the current and future direction of the wind to achieve a direction-based addressing. Another example is given by the flagellated bacteria communication, where addressing can be achieved by engineering bacteria able to sense only some types of attractants which are released only by the targeted receivers.

Conclusion

Nanonetworks will have a great impact in almost every field of our society ranging from health care to homeland security and environmental protection. In order to enable the communication among nanomachines, it is necessary to rethink existing communication paradigms and to define new communication alternatives stemming from the nature of the nanoscale. While the hardware underlying nanonetworks is still being developed, the engineering of new computing and data storage architectures for nanoscale devices, the definition of new information encoding and modulation for nanomachines using different nanocommunication paradigms, and the development of nanonetworking structures and protocols are necessary contributions expected from the ICT field.

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