Energy Harvesting in Electromagnetic Nanonetworks

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***Abstract*—This paper reviews the processes, issues, and challenges in energy harvesting in an electromagnetic nanonetwork, composed of nanonodes that are nanometers to micrometers in size. Each nanonode harvests the energy required for its operations, such as processing and communication through ambient energy sources such as fuel or vibration. To create a nanonetwork, unique characteristics of nanonodes such as nanoscale size and communication technology should be considered along the energy harvesting process. We introduce energy harvesting issues and challenges in nanonetwork related to the design and performance evaluation of a nanonetwork in terms of throughput, delay and the utilization of harvested energy. Finally, we discuss open issues in the realization of energy harvesting nanonetworks.**

I. INTRODUCTION

Recent advancements in nanotechnology have provided significant growth in small scale communication. Wireless nanonetworks [1] are an emerging generation of networks at nanoscale. A nanonode, illustrated in Figure 1, is composed of nano-sensors, nano-actuators, nano-antennas, nano-memory, a nano-transreceiver, nanoscale energy storage, nano-processors, and energy harvesters. Each nanonode is on the order of nanometers to micrometers in size. The nanoscale property of nanonodes creates the opportunity to develop intriguing new applications in the medical, biological, military, chemical, industrial, and environmental domains [1]. For example, nanonodes could recognize the presence of various chemical molecules or different infectious harmful bacteria or viruses [1]. These type of nanonodes can be deployed in various environments or inside the human body to implement drug delivery systems, for example [1]. Similarly, nanonodes could be attached to daily objects (e.g., pens, papers, clothes, etc.), facilitating the realization of the Internet of Things (IoT).

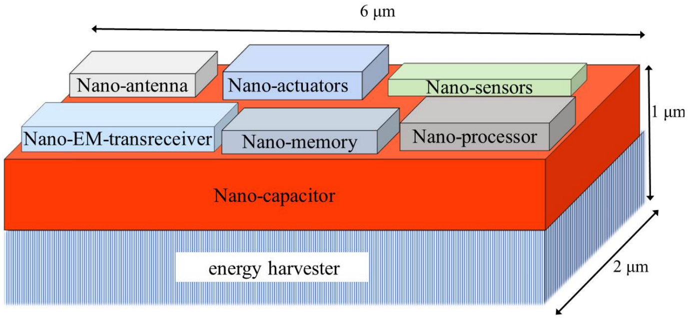

Fig. 1: Structure of an Electromagnetic (EM) Nanonode (adapted from [1])

Communication plays the main role in the realization of a nanonodes functionality. Nanonodes collect useful information and may need to transfer this information outside of the nanonetwork for additional processing. Before sending data to another network, nanonodes may need to communicate with each other as well. Nanonodes can communicate in a centralized or distributed fashion. In a centralized topology, nanonodes will communicate with a central node, called nano-controller, which provides communication with other networks, such as a body area network or a local area network. In a distributed topology, nanonodes communicate with each other. Neighbor nanonodes will forward packets between nanonodes that are not in the communication range of each other. Because communication is such a significant function of a nanonetwork, nanonodes require energy to facilitate this communication [2]. The required energy can be renewed through harvesting from ambient energy sources, such as vibration, heat, and light.

II. SOURCES OF ENERGY FOR NANONODES

In recent years, energy harvesting has attracted attention due to the availability of devices that can harvest energy from light, ambient vibrations or heat. However, some energy sources such as light or heat energy are limited to specific locations and times. The limited size of nanonodes as well as some of their applications in environments with no light (e.g. inside body or in liquids) necessitates the investigation of other energy sources in nanonetworks. Mechanical energy (from vibration and motion) and chemical energy are the two main sources of energy for nanonodes, especially in biological environments. Thermal energy is not efficient and has downsizing limitations. The following discusses state-of-art energy harvesting mechanisms for nanonodes.

A. *Mechanical Energy Harvesting*

Mechanical energy from vibration and motion is typically available in many environments. Energy harvested from home appliances (e.g., refrigerator, washing machine, etc.) to human body movements (e.g., walking, running, beating of the heart, muscle stretching) [3] makes mechanical energy a considerable source of energy in many biomedical and industrial applications of nanonetworks. Mechanical vibrations exist in a wide range of frequencies, from a few hertz to several kilohertz, which result in power densities ranging from a few microwatts to milliwatts per cubic centimeter [3].

The applicability of conventional materials such as lead zirconate titanate (PZT) is limited because of durability, reliability, and safety issues. Recently, piezoelectric nanowires, which are used to develop nano-generators, have been proposed as the main approach in the harvesting of mechanical energy for nanonodes [2]. Fabrication of nano-generators on various substrates, including semiconductors, polymers, metals and fibers [4], allow the possibility of potential applications such as smart clothes. Fiber nano-generators have been developed to harvest energy from even low-frequency vibrations induced by air or human exhalation [5].

B. Biofuel Cells (BFCs) for Harvesting Chemical and Biochemical Energy

A typical fuel cell operates by converting the chemical energy of a fuel, such as methanol or hydrogen, into electricity [6]. A chemical reaction between the fuel and an oxidizing agent, such as oxygen or air, results in producing electricity. While in batteries chemical materials store electrical energy, in fuel cells the electricity is generated directly through the chemical energy extracted from reactants. Fuel cell technology is a known method with extensive applications at macro scale. However, the conventional technology has limitations in fabrication cost, materials used, and size. Therefore, it is not possible to use traditional fuel cells in micro and nanoscale applications, such as intrabody medical sensors. To overcome these limitation, a biofuel cell (BFC) has been introduced that substitutes metals with biological enzymes as the chemical cathode and/or anode [6].

BFCs can be categorized as (i) enzymatic BFCs, where the catalytic enzymes exist outside of living cells; and (ii) microbial fuel cells (MFCs), where the catalytic enzymes exist inside of living cells [6]. Although MFCs have high fuel efficiency and long-term stability, their power densities are usually lower than enzymatic BFCs [6]. Thus, the application of MFCs at the micro and nanoscale is limited. Enzymatic BFCs are biocompatible and can provide efficient power on order of sub-mWcm^{-2}. These properties make them a desirable choice in intrabody biomedical applications, where biochemical energy can be harvested from the enzymes inside the human body. However, the state-of-art enzymatic BFCs still do not represent stable behavior.

C. Hybrid Biomechanical and Biochemical Cells

Relying only on one energy harvesting method, such as biomechanical or biochemical, results in wasting other available types of energy sources. Therefore, new research directions [7] attempt to develop innovative approaches for concurrent harvesting of energy from several types of sources via integration techniques. This will help the energy harvesting process because it will handle instability in the temporal and spatial availability of energy sources at nanoscale.

In the biological environment, muscle stretching, body motion and metabolic processes provide significant sources of mechanical and biochemical energy. Therefore, hybrid solutions of these two energy sources are emerging as a new approach for energy supply in biological environments. A hybrid energy scavenger [7] was developed recently that is composed of a piezoelectric nanogenerator and an enzymatic BFC. Mechanical energy is harvested from sources such as blood flow in the vessels, while the biochemical energy is harvested from the oxygen and glucose available in biofluids. This integrated device enables energy harvesting from both sources simultaneously. Studies [7] have demonstrated the feasibility of applying these energy harvesters in the biomedical domain to power nanosensors.

Alternative Sources of Energy More advancement in energy harvesting downscaling is required to integrate the harvesters from various sources such as light, solar, and thermal into nanonodes. For example, new photovolatic energy harvesting based on graphene is emerging [1].

Currently, energy harvesting from mechanical or biochemical sources are the main approaches to supply energy for nanodevices. These are also applicable for in vivo medical applications. New sources of energy for biochemical energy harvesting are emerging every day. For example, energy harvesting from blood sugar by biofuel cells [2] or from electrical differences in the inner ear [3] are new sources of energy.

Moreover, advancements in nanodevices can be helpful in the production of nanoscale radio frequency (RF) energy harvesters. Currently, RF energy harvesters are widely used for wireless sensor or RFID networks. With the help of nanotechnology, this could be a significant source of energy, which is also controllable. Moreover, inductive charging, which is currently deployed for many medical applications in body area networks, could be investigated. Again, the size limitation is likely the main barrier for its usage at nanoscale.

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III. THE ENERGY HARVESTING FOR NANONETWORKS PARADIGM

There are many issues to be answered before nanonetworks can be realized. Figure 2 illustrates the state of the art in electromagnetic nanonetworks at the various layers of the

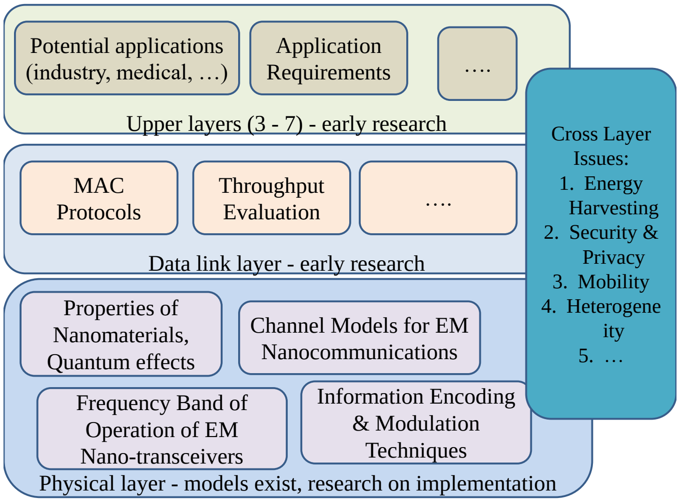

Fig. 2: State of the Art for Electromagnetic Nanonetworks at the Network Protocol Stack Layers.

network protocol stack. At the physical layer, properties of nanomaterials are known and the modeling of wireless communication in the THz band has been studied, more specifically, pulse based communication in the 0.1-10 THz - see “Pulse-based THz Communication”.

Pulse-based THz Communication

Communication in Terahertz is very sensitive to communication distance and frequency due to molecular absorption and thermal effects [1]. For distances larger than one meter in a gaseous environment with 10% water vapor, the path loss exceeds 100 dB. The path loss for 1 cm distance is around 50 dB at high frequencies, i.e. greater than 5 THz. Therefore, the power requirement for various distances and frequencies would vary significantly and should be considered in any communication design scheme. Nanonodes deploy Rate Division Time Spread On-Off Keying (RD TS-OOK) [1] as the modulation mechanism. In this modulation, a logical `0` is transmitted as silence and a logical `1` is transmitted as a femto-second long pulse. RD TS-OOK is proposed as the simple possible modulation, but it is envisioned that more complex modulations (e.g., pulse rate, pulse width, or pulse amplitude) are not feasible in nanonetworks.

[1] J. M. Jornet and I. F. Akyildiz, Information capacity of pulse-based wireless nanosensor networks, in Proceedings of IEEE SECON, 2011, pp. 8088.

The cross layer issues related to the networking of nanonodes along with the energy harvesting aspects are one of less explored areas. At the data link layer, some initial work [2], [8], [9], [10] has been done, including work on energy harvesting design. Some other issues about various layers and applications of nanonetworks in the realm of the Internet of NanoThings have also been studied [11]. Moreover, issues such as security, privacy, mobility and heterogeneity of nanonodes are other cross layer issues that should be considered in the design of nanonetworks. In this paper, we focus on issues related to the networking for energy harvesting nanonodes.

The main challenges in the networking of nanonodes with energy harvesting are illustrated in Figure 3. A network design must address all these challenges.

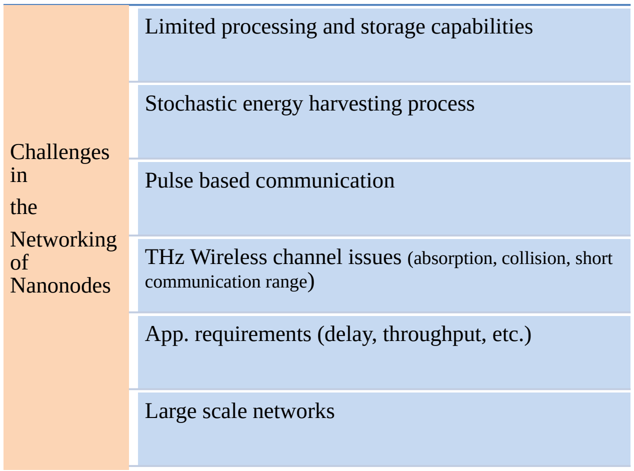

Fig. 3: Challenges in the Networking of Nanonodes.

The first issue rises from the size limitation of a nanonode and current technologies of energy harvesters and energy storage. As illustrated in Table I, the magnitude of reduction in energy storage, energy consumption (for communication) and energy harvesting rates are different from the reduction for node size. Also, note that the energy storage and energy harvesting reduction is much higher than the energy consumption reduction. Therefore, these parameters should be studied differently in energy harvesting-aware design for nanonetworks.

Moreover, the THz pulse based communication model, size limitation of nanonodes (which results in low processing capabilities), and stochastic properties of the energy harvesting process create new challenges in the design of the energy consumption process for energy harvesting nanonetworks. Because the energy is expected to be renewed, it is important to achieve the maximum utilization of this energy while keeping a nanonode operational. This differs from traditional energy-saving models in wireless sensor networks (e.g., data compression, duty cycles, data aggregation, balancing energy consumption among all nodes, etc.) although some of these techniques may still be applicable to nanonetworks.

Furthermore, specific application requirements for nanonetworks and the large scale of nanonetworks, i.e., network of thousands of nodes in a small area, are other challenges in the design of nanonetworks.

IV. MODELS AND OPTIMIZATION

There are special characteristics of nanonetworks that necessitate the development of new models for the evaluation of energy consumption and harvesting processes. More specifically, unlike other networks, the granularity of the energy harvesting rate in nanonetworks is slower than the energy consumption

TABLE I: Comparison of Microscale Networks and Nanonetworks

	Micronetwork [12]	*Nanonetwork* [2]	*Magnitude of Scale Reduction*
Power Consumption	mW	μW	3
Node Size	cm^3	μ^3	4
Energy Storage	J	pJ	12
Energy Harvesting Rate	μJ/s	pJ/s	6

rate (Figure 4). In other words, the energy harvested in a couple of seconds can actually be consumed in a couple of picoseconds. This implies that it can take up to 5 minutes to harvest energy to transmit only a small packet [2]. Moreover, new harvester elements such as nanowires present different behaviors than previously studied models, such as photovoltaic or electrostatic cells. In addition, new sources of energy are emerging. For example, energy harvesting from blood sugar by biofuel cells or from electrical difference in the inner ear - see "Alternatvie Sources of Energy"- are new sources of energy with unique properties. Moreover, nano-capacitors represent a non-linear behavior as compared to most battery-based models [2]. Finally, most models in other networks assume an unlimited energy buffer that cannot be considered in nanonetwork scenarios (Table I). All such properties mandate the need for novel models of energy harvesting and consumption for nanonodes.

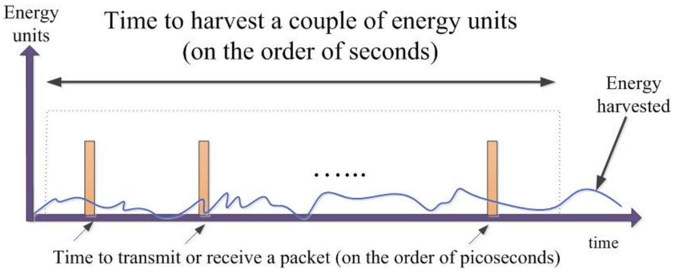

Fig. 4: Comparison of Timescales Between Harvesting and Consumption of Energy

The optimum utilization of harvested energy is another main challenge to be addressed in nanonetworks [13], [14]. This can be related to increasing throughput, decreasing delay, or increasing reliability. The goal of optimization is to develop energy harvesting-aware rather than energy-efficient methods. In energy-efficient methods, the energy budget is limited and the available energy over the total period of problem modeling should be optimized. However, in energy harvesting-aware methods, the decision about the situation depends on the amount of available energy at the moment and the prediction of energy arrival. Therefore, the optimum use of energy needs a different model.

Intuitively, to maximize energy utilization, more consumption is the best action. On the other hand, the existence of some energy is required to minimize the possibility of nanonode failure and consequently lack of communication. In this case, the question is: what are the optimal rates of energy consumption? If the harvested energy is not consumed optimally, a nanonode will miss some energy that it could otherwise have harvested. This, for example, can occur if a conservative policy (i.e., minimum consumption rate) is used. An aggressive strategy, to the contrary, will create nodes with low energy levels which will lead to many failures in packet transmission [14]. The current amount of energy and the harvesting model determine the optimal energy consumption policy. It is a challenging problem since energy arrival follows a stochastic process. Finding the packet size and/or feasible transmission rates to satisfy the optimal rates make the problem even more difficult.

Furthermore, optimum energy consumption for nanonetworks should include specific characteristics in their design. More specifically, energy storage for nanonodes is not unlimited or very large, energy harvesting and consumption rates are not similar, and finally the complex models cannot be run in resource limited nanonodes. Moreover, given that nanonodes may be in unknown environments, they need to adapt their energy consumption based on the available energy for harvesting. Adaptive optimization models to maximize the utilization of harvested energy typically result in computationally expensive schemes. Since the processing and memory resources are limited in the nanonodes, the optimum solutions should be designed as offline solutions. Another approach to consider is to develop light-weight heuristic methods with near-optimal performance [14].

The optimization of energy consumption remains an open issue in several aspects in nanonetworks. Solutions are needed that consider the application requirements, energy harvester models that harvest from multiple sources, heterogeneous nanonodes (i.e., nanonodes with various energy storage capacities or various type of harvesters) and various traffic (point to point, multicast, broadcast) models.

Another aspect in maximizing the utilization of energy is to consider energy consumption for other processes besides communication. Since the capacity of a nanonode's energy storage is very small, sensing and actuation as well as information processing can be considerable sources of energy consumption. Moreover, energy utilization for nonlinear storage models is another open area for further investigation.

V. PROTOCOLS

Similar to the reasoning about the need for new models of energy harvesting in nanonetworks, energy harvesting-aware protocols need to be customized and may even be newly created. Pulse-based communication in the THz band, the unique properties of energy harvesting and consumption for nanonodes, and the capability limitations due to size constraints are the main factors that mandate the development of novel energy harvesting-aware protocols.

Medium access control (MAC) design is the main issue to be addressed. Energy harvesting-aware MAC protocols for nanetworks [8], [15] attempt to design a light-weight protocol to enable implementation on resource limited nanonodes and also provide scalability. To achieve this goals, a nano-controller is proposed to operate as a central controller. Moreover, it can provide optimal and fair channel access among all nanonodes when all nanonodes try to access the medium. The MAC protocol on the nano-controller controls the packet scheduling of transmissions. Also, these models provide a threshold for the minimum energy requirement to allow operational conditions of such a system.

Another type of energy harvesting-aware MAC protocol (RIH-MAC) has been proposed [9], [10], where nanonodes communicate based on a receiver-initiated mechanism. The advantage of this protocol is that through a receiver-initiated mechanism, the harvested energy is utilized more efficiently because the transmitter and receiver spend their energy wisely to maximize the probability that both the transmitter and receiver will have energy for communication. Moreover, this allows to use RIH-MAC either in a centralized network topology or in an ad hoc formation of nanonodes, i.e., in a distributed network topology. The distributed RIH-MAC protocol (DRIH-MAC) exploits a distributed edge-graph coloring scheme to provide a scalable solution for coordination among nanonodes to access the medium. Each Nanonode selects a different color (i.e., timeslot) for communication with each of its neighbors. In the coloring process, each nanonode only communicate with its neighbors. Therefore, the solution is distributed and consequently scalable. Although the timeslot for each two neighbors will be fixed, the packet exchange in that timeslot could be unsuccessful due to lack of energy at either side. To minimize that, a model is developed to predict the energy level of neighbors. The performance evaluation shows that the model decreases the probability of unsuccessful communication between neighbor nanonodes due to lack of energy.

These protocols are the first steps towards energy harvesting-aware protocols for nanonetworks. More protocols for the MAC layer as well as upper layers remain open for further investigation. Methods other than receiver-initiated protocols for communication that consider energy harvesting as well as scalability of solutions for nanonetworks are of interest. In the network layer, creating a hierarchical architecture for node addressing and information routing is required. Still, it should addresses scalability and energy harvesting. These consideration will affect the performance at the application layer. Reliability and delay requirements of the applications will be the main challenges.

Another area of research would be considering mobile nanonodes. Mobility will create a dynamic topology, which affects protocol design in all layers. Particularly, designing medium access mechanism as well information routing become more challenging. Moreover, a dynamic topology will result in a variable traffic model, and consequently various energy consumption models for nanonodes. Furthermore, satisfying application requirements (e.g., delay, packet delivery success rate), for mobile energy harvesting nanonodes becomes challenging. Therefore, energy harvesting-aware protocols should consider mobility in their design.

VI. CHALLENGES IN EMERGING APPLICATIONS

Several applications can be considered for nanonetworks in the medical, biological, military, chemical, industrial, and environmental domains, for instance. The operational environment for these applications varies significantly, from inside the human body to chemical materials in an industrial environment. These properties in addition to characteristics of nanonetworks raises several questions. 1) To what extent will protocols be portable from one application to another? 2) To what extent can optimal energy consumption strategies be used for various applications? 3) Various applications will have various traffic rates, i.e., information generation, information exchange. How would these traffic rates affect the performance of protocols and models? 4) Would limitations on the energy harvesting paradigm in nanonetworks limit the feasibility of any of these applications? In the following, we explore some of these questions in more detail for some applications.

One of the applications of nanonetworks is the Internet of nano-Things (IonT). The smaller size of nanonodes, which makes it simpler to be integrated with daily things, as well as the low energy consumption of nanonodes could be a significant motivation to develop IonT. The performance evaluation of methods and protocols that have been developed so far for nanonetworks with the operational conditions of things would be of interest. Other requirements such as mobility and a hierarchical structure to address scalibility are open for further investigation.

Another application of nanonetworks is to create a network among nano-robots [16]. Nano-robots, which are also called programmable matters or utility fogs, are a collection of tiny self-organized and self-configured robots. They coordinate with each other to accomplish the mission on demand. Having the abilities of coordinated self-assembly and self-reconfiguration could allow nano-robots to adapt to different environments on-the-fly. For example, they are particularly well suited to situations in which they must adapt to tasks not known *a priori* such as search and rescue applications in unstructured environments, planetary exploration, and deep space exploration. Sometimes, these nano-robots have the potential to exploit self-healing abilities with a reserve supply of low cost robot modules.

THz communication is a very desirable candidate method of communication between nanorobots since the energy consumption for communication in the range of centimeters is very low. The new nature of communication between a collection of self-organized nanorobots in addition to the structure of a very dense network necessitate the development of new protocols for communication among them. Moreover, if the mission is long, they may rely on energy harvesting. Therefore, again an energy harvesting-aware design is required. The impact of mobility on network design and energy consumption becomes a major issue for nano-robots.

Wireless Network-on-Chip (WNoC) could be a major application for nanonetworks. Designing the network based on the application of WNoC is an open question. WNoC may not necessarily form a grid or mesh network because of the nature of the application. Therefore, the evaluation of current MAC protocols or tailoring it for other topologies is an interesting topic to explore. Also, since the nanonodes could change their communication range to be able to communicate with various nodes at different times, this could open up new opportunities for more sophisticated protocols for communication among nanonodes. For example, this could include increasing the communication range for broadcast communication and reducing it for point to point communications when nanonodes are deployed as WNoCs.

VII. CONCLUSION

Energy harvesting in nanonetworks is the key enabler for their application in various domains. Nanonodes are expected to harvest their required energy mainly from ambient sources. Harvested energy has to be utilized for the optimum performance of the nanonetwork for nanonodes that have nanoscale limitations, new communication models, and limited energy storage. Solving the issues and challenges at the various network layers will enable the realization of nanonetworks.

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