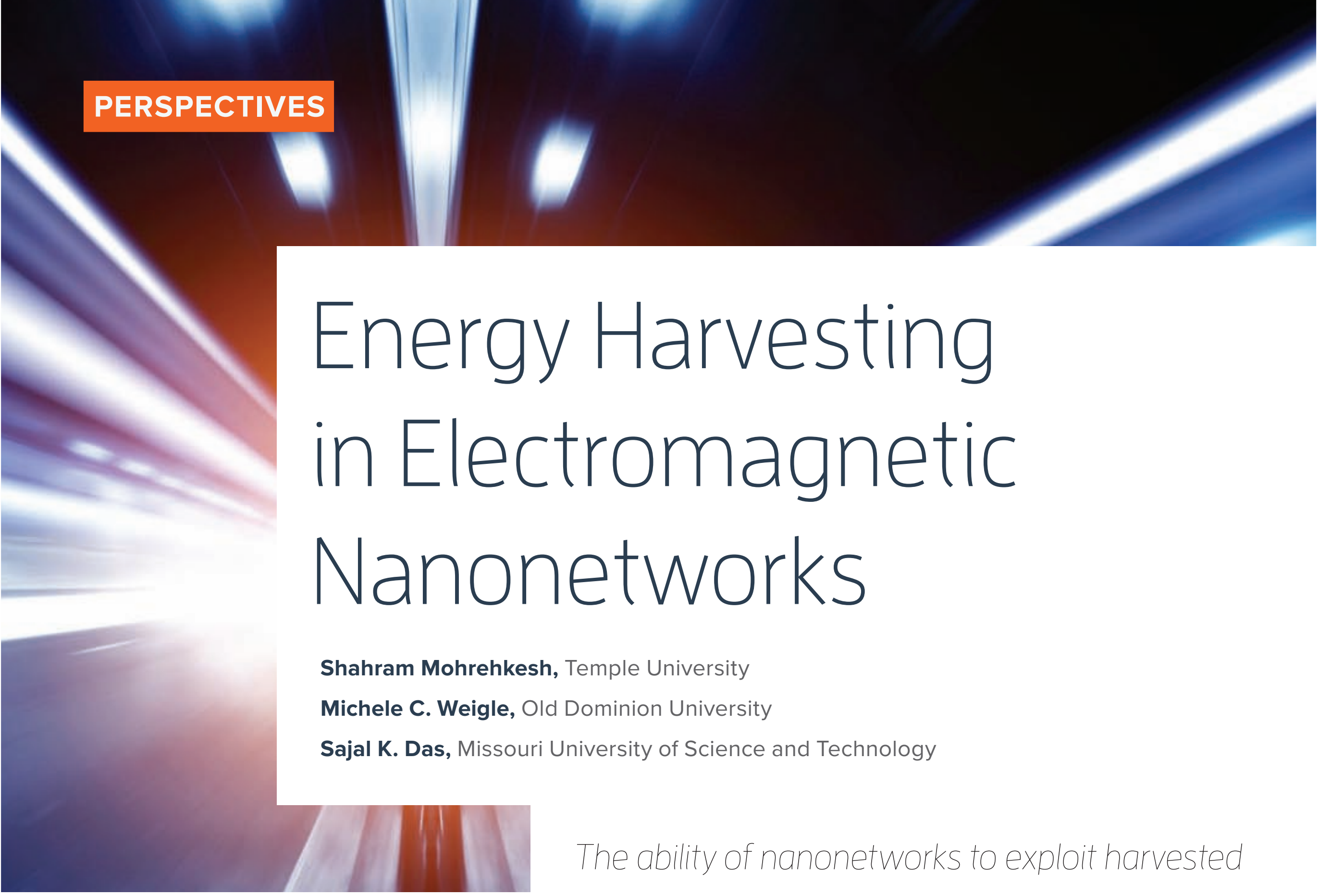

Energy Harvesting in Electromagnetic Nanonetworks

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The ability of nanonetworks to exploit harvested energy from ambient sources efficiently and economically will determine the extent of their future application. Research has already identified processes, issues, and challenges for these networks, most of which center on the energy-harvesting process, optimal energy consumption, and communication protocols.

Recent advancements in nanotechnology have boosted growth in small-scale communication to the point that wireless nanonetworks are already emerging.[1] As Figure 1 shows, a nanonode is composed of various nanocomponents—from nanosensors to nanoprocessors—and is fabricated as small as a micrometer device. The nanoscale property of these devices creates the opportunity to develop novel and intriguing applications in medical, biological, military, chemical, industrial, and environmental domains. In envisioned applications, nanonodes will recognize the presence of various chemical molecules or different infectious harmful bacteria or viruses or will be deployed in novel operating environments, such as the human body, to perform missions on demand, such as implementing drug delivery. Attached to familiar objects, like pens, paper, or clothing, they will help facilitate the Internet of Things (IoT).[1]

Electromagnetic communication, particularly in the THz frequency band, will be the primary driver in realizing nanonodes' functionalities because nanonodes collect and process a variety of useful information by communicating with one another. Also, their limited processing and storage requires them to transfer data to another network for further processing. Communication is either directly between nodes in an ad hoc manner or through a nanocontroller, a central node that communicates with other networks, such as a LAN. Communication in all its forms will require energy, which nanonodes acquire by harvesting energy from ambient sources, such as vibration, heat, and light.[2]

Researchers have already identified the processes and issues involved in energy harvesting in an electromagnetic nanonetwork, including those related to the nanonetwork's design and performance evaluation in terms of throughput, time to harvest energy, and efficiency of energy use. This work underlines both the ongoing challenges of energy harvesting and its potential to enable promising new applications.

ENERGY SOURCES FOR NANONODES

Energy harvesting has attracted attention because devices to acquire energy from light, heat, or vibrations

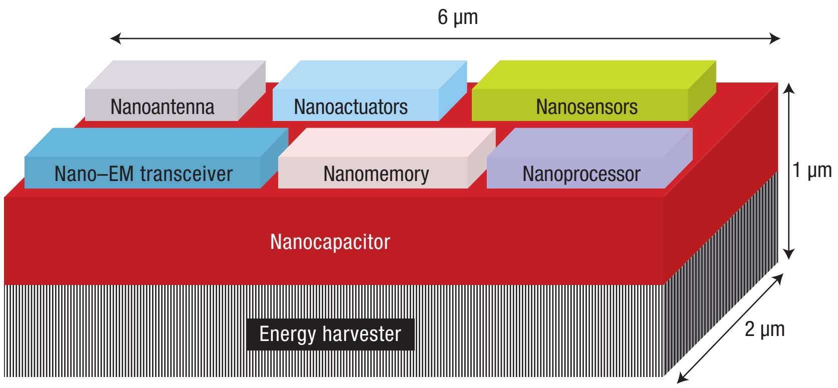

FIGURE 1. Structure of an electromagnetic nanonode (EM). Harvested energy is stored in the nanocapacitor to supply power for other nanocomponents.

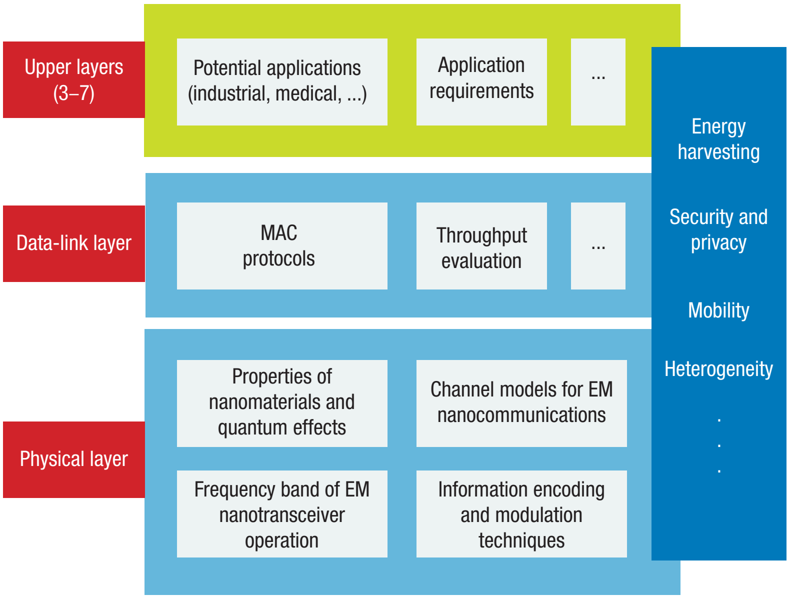

FIGURE 2. State-of-the-art for EM nanonetworks at various layers of the network protocol stack. Research in most layers is in the early stages, with efforts that focus on implementation issues still only at the physical layer. MAC: medium access control.

have been readily available. However, the amount of energy that can be harvested from certain sources often depends on location and time. Nanonode applications, for example, might involve operational environments with no light, such as in liquids or deep space. Thermal energy is also inefficient and has downsizing limitations. These disadvantages have motivated investigation into alternative sources, such as mechanical and chemical, which are compatible with nanonodes' requirements, particularly those in biological environments. More recent efforts have explored hybrids of biochemical and chemical energies. As the sidebar "Alternative Energy Sources" describes, these hybrids have potential but at present are less feasible for energy harvesting.

Mechanical

Mechanical energy from vibration and motion exists in many entities, from home appliances to the human body. Energy generated from walking, running, or heartbeat could fuel many biomedical and industrial nanonetwork applications. Mechanical vibrations have a wide range of frequencies, from a few hertz to several kilohertz, which yield power densities of a few microwatts to milliwatts per cubic centimeter.[3]

Conventional materials such as lead zirconate titanate (PZT) are not inherently useful as energy harvesters because they are not sufficiently durable, reliable, or safe in that application, so researchers have had to look elsewhere for suitable mechanical-energy harvesters. Recently, piezoelectric nanowires, which are used to develop nanogenerators, have been proposed as the primary means of harvesting mechanical energy.[2] Fabricating nanogenerators on various substrates, including semiconductors, polymers, metals, and fibers,[4] could enable applications such as smart clothing. Some proposed fiber nanogenerators can harvest energy from even low-frequency vibrations, such as those in air flow or exhalation.[5]

Chemical and biochemical

Chemical and biochemical energies, harvested through biofuel cells (BFCs), are also potential sources, and BFCs address many incompatibilities of traditional fuel-cell technology for nanonodes.

Drawbacks of fuel cells. 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 air, produces electricity. While in batteries, chemical materials store electrical energy; in fuel cells, electricity is generated directly through the chemical energy extracted from reactants.

ALTERNATIVE ENERGY SOURCES

At present, energy-harvesting technology is not mature enough for nanodevices to draw energy from sources other than mechanical and biochemical. More advances in downscaling energy harvesting are necessary to integrate harvesters of light, solar, and thermal energy into nanonodes. For example, new photovolatic energy harvesting based on graphene is emerging.[1]

Energy harvesting from biochemical sources is already part of in vivo medical applications, such biofuel cells that draw energy from blood sugar[2] or from electrical differences in the inner ear.[3]

Advances in nanodevices can also 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 nanotechnology, RF energy could be a significant and controllable source.

Another possible energy source is inductive charging, which is currently deployed for many medical applications in body area networks. However, the size limitation is likely the main barrier for its use at nanoscale.

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Fuel-cell technology is a known method with extensive applications at the macro scale, but fabrication cost, lack of usable materials, and size make it ill suited for micro- and nanoscale applications, such as intrabody medical sensors.

Types of biofuel cells. BFCs substitute the metals in traditional fuel cells with biological enzymes, which serve as the chemical cathode, anode, or both. In *enzymatic* BFCs, catalytic enzymes exist outside living cells. In another BFC type, *microbial fuel cells* (MFCs), catalytic enzymes exist inside living cells. Although MFCs have high fuel efficiency and long-term stability, they are less efficient at micro- and nanoscale because their power densities are usually lower than those for enzymatic BFCs.[6]

In contrast, enzymatic BFCs are biocompatible and can efficiently provide power on the order of milliwatts per square centimeter (mW/cm^2). These properties make them a desirable choice in intrabody biomedical applications, in which biochemical energy can be harvested from the enzymes inside the human body. However, state-of-the-art enzymatic BFCs still do not exhibit stable behavior.

Hybrid biomechanical–biochemical cells

Relying on only one energy-harvesting method, such as biomechanical or biochemical, misses the opportunity to tap other available energy sources. To correct this inefficiency, recent research efforts are exploring approaches that use integration techniques to enable energy harvesting from several sources concurrently.[7] Concurrent harvesting has a strong advantage for energy harvesting because it can handle instability in the temporal and spatial availability of energy sources at nanoscale.

In a biological environment, muscle stretching, body motion, and metabolic processes are significant sources of mechanical and biochemical energy, and hybrid solutions of these two sources are emerging. One proposal describes a hybrid energy scavenger[7] composed of a piezoelectric nanogenerator and an enzymatic BFC. Mechanical energy is harvested from sources such as blood flow in the vessels, while biochemical energy is simultaneously harvested from the oxygen and glucose available in biofluids. Studies have demonstrated the feasibility of applying these energy harvesters to power biomedical nanosensors.[7]

NANONETWORK MATURITY

Figure 2 illustrates nanonetwork developments in the context of the network protocol stack. Currently, developments at the lowest level, the physical layer, are the most mature. Nanomaterial properties are known, and researchers are studying models of wireless nanonode communication in the THz band.

At the data-link layer, some initial work has been done, including studies of requirements for energy harvesting–aware design.[2,8–10] At least one effort has explored issues in

TABLE 1. Comparison of energy specifications for nodes in microscale networks and nanonetworks.

Dimension	Micronetwork	Nanonetwork	Magnitude of scale reduction
Power consumption	mW	μW	3
Node size	cm^3	$μm^3$	4
Energy storage	J	pJ	12
Energy-harvesting rate	μJ/s	pJ/s	6

nanonetworks as part of building the Internet of Nano Things (IoNT).[11]

Less work has been devoted to exploring the cross-layer issues, such as security, privacy, mobility, and heterogeneity. Heterogeneous nanonodes are those with a variety of energy-storage capacities or harvester types.

DESIGN CHALLENGES

Research so far has identified three main areas of challenge for networking nanonodes with energy harvesting:

- developing efficient and economical processes for energy harvest and storage;
- coping with THz communication's sensitivity to frequency and distance; and
- identifying new applications and their performance requirements.

These must be addressed when designing the consumption process for energy-harvesting nanonetworks. Because nanonodes are expected to renew the energy they harvest, the goal is to achieve maximum energy use while keeping a nanonode operational. This objective differs from the aims of traditional energy-saving models in wireless sensor networks, which rely on data compression, duty cycles, data aggregation, and balanced energy consumption among nodes. It remains to be seen if any of these traditional models and techniques will be useful for nanonetworks.

Harvest and storage

The harvest and storage challenge stems from the nanonode's size restriction, the immaturity of current energy harvesters, and the stochastic nature of the energy-harvesting process. Although energy harvesting follows a stochastic model for micronetworks, new energy sources can cause the energy-harvesting process to exhibit new stochastic behaviors. For example, the amount of energy harvested from body motion varies according to the activity's type, duration, and intensity. Also, energy-harvesting specifications vary from micronetworks to nanonetworks, as the comparison in Table 1 shows.[2,12] The magnitude of reduction in energy storage, energy consumption for communication, and energy-harvesting rates differs according to node size, with energy-storage capacity and energy-harvesting rates decreasing faster than power consumption. These parameters appear to be unique for nanonetworks with energy harvesting, and any energy harvesting–aware design must take their interrelationship into account.

Communication issues

Unsuccessful communication—the failure to transmit or receive packets—results when a nanode uses harvested energy inefficiently. Communication in the 0.1- to 10-THz range is extremely sensitive to communication distance and frequency because of molecular absorption and thermal effects, which cause high signal loss and subsequent unsuccessful packet transmission or reception.[13] For example, for distances larger than one meter in a gaseous environment with 10 percent water vapor, the path loss exceeds 100 dB. The path loss for 1 cm distance is around 50 dB at frequencies greater than 5 THz. Therefore, the power requirement for various distances and frequencies will vary significantly and should be considered in any communication design scheme.

Pulse-based communication has been proposed as a way to mitigate the high loss in a THz communication channel, in which nanonodes deploy rate division time spread on-off keying

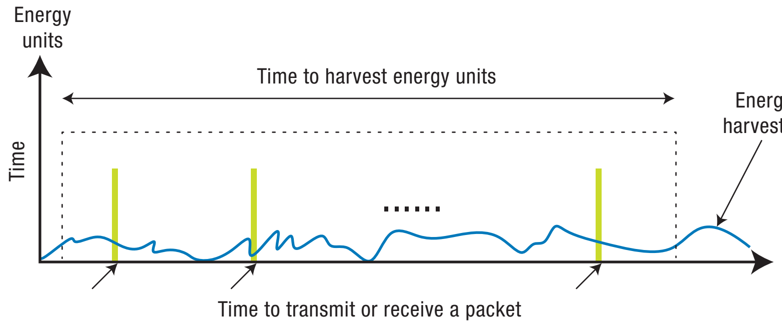

FIGURE 3. Comparative timescales for energy harvesting and consumption. The seconds of time to harvest only a few energy units is far longer than the picoseconds it takes a nanonode to receive or transmit even a small packet (vertical bars). Thus, the energy consumed in communication far outpaces what the nanonode can harvest. This imbalance is a major challenge in designing nanonetworks with energy harvesting.

(RD TS-OOK) as the modulation mechanism.[13] In this modulation, a logical 0 is transmitted as silence and a logical 1 is transmitted as a femtosecond-long pulse. RD TS-OOK is proposed as a simple modulation, but more complex modulations, such as pulse rate, width, or amplitude, are not feasible in nanonetworks.

Application requirements

Accommodations for application requirements such as delay and throughput should be part of nanonetwork design along with energy-consumption policies. Finding this tradeoff becomes more challenging when the nanonetwork consists of thousands of nodes in a small area because complicated solutions would not be scalable for such a large network.

NEED FOR NEW MODELS

Nanonetworks' special characteristics necessitate the development of new models for evaluating energy consumption and harvesting. For example, relative to traditional networks, nanonetworks harvest energy more slowly than they consume it, as Figure 3 shows. For example, the energy harvested in a few seconds can be consumed in a few picoseconds, which implies that it might take up to 5 minutes to harvest the 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, and new energy sources are emerging with their own unique properties and behaviors. Other examples of nontraditional behaviors and characteristics include nanocapacitors, which exhibit a nonlinear behavior[2] atypical of most battery-based models, and the lack of an unlimited energy buffer in nanonetworks, which most conventional network models include. These differences call for novel models of energy harvesting and consumption.

OPTIMIZING ENERGY USE

The optimum use of harvested energy is a critical requirement that could affect the application's throughput, delay, or reliability.[14,15] However, optimizing energy use in a network is nontraditional in that the primary aim is to develop methods that are energy harvesting–aware. This objective contrasts sharply to energy-efficient methods, which must cope with a finite energy budget and thus seek to optimize the consumption of available energy over the application's lifetime. In energy harvesting–aware methods, optimization depends on the amount of available energy at a given moment as well as on predictions of when energy will arrive. Modeling optimal energy use with these dependencies requires new techniques.

Optimal models

At first glance, aiming for optimal harvested energy use would appear to be the best approach. However, the energy-harvesting process must be taken into account or, in certain scenarios, such as when nanonodes attempt to transmit and receive at fixed rates and are not aware of the energy amount at their neighbor nanonodes, the nanonodes will fail to communicate successfully.[15] Thus, rather than finding optimal energy use, the problem becomes finding the optimal energy-consumption rate, which involves accounting for harvesting properties, such as harvesting rate and harvester specification, as well as communication requirements, such as the transmission-and-reception schedule and required energy for communication.

With a minimum consumption rate, a nanonode might miss some energy that it could otherwise have harvested. On the other hand, aggressive consumption would lead to some nanonodes having low energy levels, which in turn could cause packet-transmission failures.[15] Ultimately, the amount of energy at a particular moment and the particular harvesting model will determine the optimal energy-consumption policy.

The problem of finding the optimal consumption point is complicated by the stochastic nature of energy arrival and the need to find a packet size and transmission rate that will satisfy that point. Moreover, energy storage for nanonodes is not unlimited or even very large, energy harvesting is slower than consumption, and complex models cannot be run in resource-limited nanonodes.

Furthermore, because nanonodes might be deployed in unknown environments, such as space, they must be able to adapt their consumption according to the energy available for harvesting. Adaptive optimization models to maximize the use of harvested energy typically result in computationally expensive schemes, and nanonodes have finite processing and memory resources. Consequently, adaptive optimization solutions should aim to be offline. Developing lightweight heuristic methods with near-optimal performance is another path to adaptive optimization solutions.[15]

NANONODES' SIZE AND LOW ENERGY CONSUMPTION MAKES THEM IDEAL FOR INTEGRATION IN EVERYDAY OBJECTS SUCH AS CLOTHING.

Other aspects

Optimizing energy consumption in nanonetworks remains an open issue, and solutions are needed that consider application requirements, energy harvester models that harvest from multiple sources, heterogeneous nanonodes, and various traffic models, such as point to point, multicast, and broadcast.

Given a nanonode's very small energy storage, the energy consumed by sensing and actuation and by information processing can be significant, which implies the need for energy-consumption solutions that take these processes into account. Energy use for nonlinear storage models is another open area worth investigating.

PROTOCOL CREATION AND CUSTOMIZATION

Energy harvesting in nanonetworks requires not only new models but also new energy harvesting–aware protocols. Pulse-based communication in the THz band, the unique properties of energy harvesting and consumption, and size constraints dictate the need to develop novel protocols.

MAC protocols

Medium access control (MAC) protocols for the design of nanonetworks that are energy harvesting–aware must be lightweight to enable implementation on resource-limited nanonodes and scalability.[8,16] A MAC protocol, which has been developed for a centralized topology, achieves both goals because the nanocontroller can provide optimal and fair channel access among all nanonodes trying to access the medium. The proposed MAC protocol on the nanocontroller controls the packet scheduling of transmissions and defines a threshold for the minimum energy requirement to allow a nanonetwork's continual operation, preventing interruptions from the lack of sufficient energy.

In another energy harvesting–aware MAC protocol, Receiver-Initiated Harvesting MAC (RIH-MAC),[9,10] nanonodes communicate through a receiver-initiated mechanism, in which the receiver nanonode announces to the transmitter that it is ready to receive a packet. The protocol maximizes the probability that both the transmitting and receiving nanonodes will have energy for communication and thus harvested energy is used more efficiently.

In addition, the RIH-MAC protocol can be deployed in either a centralized network topology or an ad hoc nanonode formation (distributed topology). The distributed RIH-MAC protocol (DRIH-MAC) exploits a distributed edge-graph coloring scheme to provide a scalable solution for coordinating nanonodes attempting to access the medium.[10] A nanonode selects a different color (timeslot) for communication with each of its neighbors. Although the timeslot for each neighbor pair will be fixed, the packet exchange in that timeslot could be unsuccessful because one or the other nanonode in the pair might have insufficient energy to complete the exchange. To minimize the chance that this will occur, a model running on the nanonode predicts the neighbor's energy level. An evaluation of the protocol's performance shows that this model decreases the probability that neighbor nanonodes will have insufficient energy to communicate.[10]

Upper-layer and cross-layer protocols

MAC protocols represent first efforts to develop energy harvesting–aware protocols for nanonetworks. Protocols for upper layers have yet to be created, and any proposed methods must consider both energy harvesting and solution scalability. In the network layer, efforts need to focus on developing a hierarchical architecture for node addressing and information routing that addresses scalability and energy harvesting. These functionalities will also affect performance at the application layer, with application reliability and delay requirements being significant obstacles.

Another aspect of protocols is mobility. Mobility will create a dynamic topology, which will affect protocol design in all layers, particularly the design of a MAC mechanism, and greatly influence information routing. A dynamic topology will result in a variable traffic model, and by extension a variety of energy-consumption models for nanonodes. Satisfying application requirements for mobile energy-harvesting nanonodes, such as delay and packet-delivery success rate, will be challenging.

APPLICATIONS

Nanonetworks have unique characteristics that can support applications in a broad domain range with widely varying operational environments, which gives rise to four important questions:

- To what extent will protocols be portable from one application to another?
- To what extent can optimal energy-consumption strategies be used across applications?
- How would traffic rates affect the performance of protocols and models?
- Will limitations on energy harvesting make certain applications less feasible?

Internet of Nano Things

Nanonodes' size makes them ideal for integration in familiar objects like clothing, and their low energy consumption is a strong advantage in IoNT applications. Evaluating the performance of the methods and protocols developed for nanonetworks under the operational conditions of the connected objects would be revealing. Other requirements such as mobility and a hierarchical structure to address scalability are avenues for additional exploration.

Nanorobot network

A nanonetwork might also be used to form a network of nanorobots, a collection of tiny self-organized and self-configured robots (also called *programmable matters* or *utility fogs*) that coordinate with each other to accomplish a given mission on demand.[17] Having the ability to coordinate in self-assembly and self-reconfiguration manners would allow nanorobots to deal with different environments on the fly. They are particularly well suited for situations that require adapting to tasks not known a priori, such as search-and-rescue missions in unstructured environments and planetary and deep-space explorations. At times, nanorobots have the potential to exploit self-healing abilities with a reserve supply of low-cost robot modules.

THz communication aligns well with a dense nanorobot network because very little energy is consumed when communicating nanobots are centimeters apart. Communication among self-organized entities in such a network will require new methods and protocols, and, if the mission is long, nanorobots might have to rely on energy harvesting, requiring a design that is energy harvesting–aware. The impact of mobility on network design and energy consumption will also be a major concern.

Wireless network on a chip

A wireless network on chip (WNoC) could be another significant nanonetwork application. A WNoC might not necessarily form a grid or mesh network topology with point-to-point communication, as in an any-cast or broadcast communication model in an ad hoc topology. Therefore, efforts should explore tailoring current MAC protocols for WNoC applications. Also, because nanonodes could change their communication range to reach various nanonodes at different times, it is worth exploring new opportunities for more sophisticated communication protocols. These might include increasing communication range for broadcasting and reducing it for point to point when nanonodes are deployed as WNoCs.

Energy harvesting in nanonetworks will be the key enabler for their application in various domains. Nanonodes are expected to harvest their required energy mainly from ambient sources and must be able to use it in a way that ensures their continued operation. Nanonodes have size limitations, unique communication requirements, and limited energy storage. Solving the issues and challenges that these characteristics present at various network layers will make it possible to move forward with novel and life-changing nanonetworks and their applications. C

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