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Wireless Sensor Networks with Energy Harvesting

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Abstract: *Wireless Sensor Networks (WSNs) are crucial in supporting continuous environmental monitoring, where sensor nodes are deployed and must remain operational to collect and transfer data from the environment to a base-station. However, sensor nodes have limited energy in their primary power storage unit, and this energy may be quickly drained if the sensor node remains operational over long periods of time. Therefore, the idea of harvesting ambient energy from the immediate surroundings of the deployed sensors, to recharge the batteries and to directly power the sensor nodes, has recently been proposed. The deployment of energy harvesting in environmental field systems eliminates the dependency of sensor nodes on battery power, drastically reducing the maintenance costs required to replace batteries. In this article, I review the state-of-the-art in energy-harvesting WSNs for environmental monitoring applications, including Animal Tracking, Air Quality Monitoring, Water Quality Monitoring, and Disaster Monitoring to improve the ecosystem and human life. In addition to presenting the technologies for harvesting energy from ambient sources and the protocols that can take advantage of the harvested energy, the present challenges that must be addressed to further advance energy-harvesting-based WSNs, along with some future work directions to address these challenges.*

Keywords: Energy-Harvesting Wireless Sensor Networks (EH-WSNs), WSN Nodes,

I. INTRODUCTION

Wireless sensor networks (WSNs) are typically used to obtain information about environments that is needed for decision making. In this context, “environmental monitoring” may refer to observation of indoor or outdoor spaces, whether natural or man-made. Relevant approaches include remote sensing using aircraft and satellites, laboratory analysis of field-collected samples, and in-situ monitoring using sensor devices and networks. They monitor chemical, biological or population-related parameters of the environments under surveillance [1]. As an example, illustrates a suite of variables monitored in the context of terrestrial ecosystems. Such environments represent a wide range of environmental energy regimes, from rainy seasons in tropical rain-forests to polar nights in Arctic deserts. The development of environmental monitoring nodes still poses many research challenges. EWSNs are often deployed far from inhabited canters, and thus without access to mains electricity [2]. This is at the root of the primary challenge: the selection of an appropriate topology and suitable operating strategies [1] that ensure the energy efficiency of the nodes [3]. In some applications, energy efficient design can be supplemented with energy-for-data trade-off [4], allowing the extension of node operational life, albeit at the cost of sub-optimal data collection rates.

These environmental monitoring WSNs, also called “field systems,” oftentimes consist of a number of sensor nodes distributed in the environment along with a local gateway node that gathers the data for storage or to transmit the data to a remote server. In these systems, the sensor nodes are low-cost, battery-operated devices with the ability to sense the specific environmental parameters required by the application and transfer the collected data to the local gateway for processing and storage. Hence, a sensor node consists of the sensor(s), a wireless transceiver, a micro- controller, memory, and a battery to power the node. When running on batteries, the limited lifetime of the sensor nodes is one of the main challenges in implementing WSNs for environmental monitoring applications. In many of these applications, it is difficult to change the batteries of the nodes regularly, and hence once a sensor node depletes its battery, that node can be considered dead. Over the years, researchers have focused on designing energy saving techniques to minimize the energy consumption of the sensor nodes at the physical (PHY), medium access (MAC), and routing layers. However, even with very energy efficient sensing and communication protocols, once the limited battery energy is exhausted, the sensor node can no longer participate in the network operations. To address the challenge of the limited energy supply to sensor nodes powered by batteries, new WSN platforms that support the harvesting of energy from the immediate surroundings have been developed. These devices are able to capture small amounts of energy that would have been lost as heat, light, sound, vibration, within the environment. By recharging the battery with energy harvested from the environment, and by developing energy harvesting aware protocols that support so-called “energy-neutral operation,” theoretically, WSNs could have infinite lifetime. Several researchers have explored technologies to harvest energy from natural sources, such as the sun, wind, and water flow, to power the sensor nodes, while others have explored man-made sources of energy, such as human walking, magnetic fields, high-frequency vibrations, and RF fields Starting from the early 2000’s several researchers have conducted surveys in the area of WSNs and Energy-Harvesting WSNs (EH-WSNs), pointing out the various energy sources, storage technologies, communication network operations, and specific implementation areas where sensor networks are applicable and deployable, which describes the design implications of powering WSNs via energy harvesting. Here, the authors present a survey on energy-harvesting sources, mechanisms, and architectures, discussing the two main sensor node architectures (i.e., harvest-use and harvest-store-use), techniques for converting different energy sources to electrical energy.

II. Motivation

While all of the research on energy-efficient protocols has helped to prolong the lifetime of WSNs, for environmental monitoring applications, it is vital to ensure continuous operation without the need to change batteries. Achieving this goal requires the adoption of novel technologies, such as energy harvesting, which opportunistically acquires energy from solar, wind, mechanical vibrations, magnetic or RF fields to recharge the node batteries. Recent advances in these energy-harvesting technologies, and the commercialization of sensor nodes that support energy harvesting, have led to a new class of WSNs, referred to as Energy-Harvesting WSNs (EH-WSNs). The ability of EH-WSNs to power the sensor nodes through ambient energy sources has led to a shift in the design requirements and goals of these networks, as network lifetime is, ideally, no longer an issue. Instead, the goal in EH-WSNs is to support energy-neutral operation, so that the EH-WSN can operate continuously using the harvested energy.

Energy harvesting provides new opportunities as well as challenges for the design of the protocols and algorithms to support environmental monitoring. In particular, rather than focusing narrowly on reducing the node energy consumption to extend network lifetime, as is the key design metric in traditional WSNs, in EH-WSNs it is important to re-consider the impact of performance metrics such as energy-efficiency, fairness, scalability, and latency in the presence of energy flow into the network. Similarly, physical, MAC and routing protocols need to be re-designed to optimize the rate at which the energy is used, rather than simply minimizing the total energy expenditure. Given the above, it is important to clearly define the performance metrics and design requirements that impact EH-WSNs, given that energy is no longer limited in the same way. Hence, in this article, we survey the current state-of-the-art techniques for harvesting energy for WSNs as well as the latest protocols and algorithms that optimally utilize this harvested energy to support the application goals and provide continuous environmental monitoring.

III. Energy Sources

In general, the goal of energy harvesting is to convert energy from one form to another that can be used to power electronic devices. When implemented in environmental monitoring nodes, it can directly extract ambient energy from the environment under surveillance and use it to power the nodes of the WSN, improving their performance and/or extending their lifetime. Outdoor environments offer plenty of opportunities to take advantage of the elements naturally present in the surroundings, such as wind or sun. However, there are also other types of energy, such as radio frequency (RF) signals resulting from human activities that be scavenged and used to power the nodes. This section provides a systematic overview of common harvesting sources suitable for environmental monitoring nodes, and their comparison. Energy harvesting sources can be categorized as ambient or external [5]. The ambient sources are accessible within an environment without any external energy supply. They include, for example, radio frequency (RF), solar, thermal, flow-based, and vibration energy harvesting sources [6]. The external sources emit energy to the environment, with the intent for this energy to be harvested by the nodes. Examples include human or mechanical sources, which are not suitable for environmental monitoring purposes.

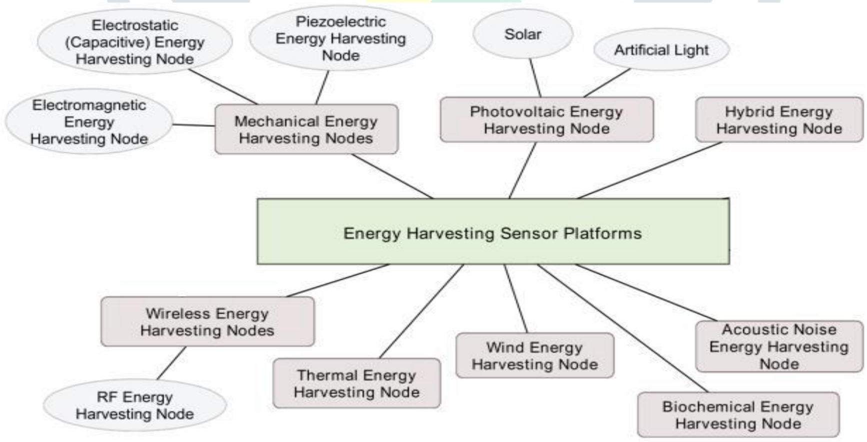

Figure 1: Different Energy harvesting methods in WSN Nodes

Mechanical energy harvesting:

Mechanical energy harvesting Indicates the process of converting mechanical energy into electricity by using vibrations, mechanical stress and pressure,[7] strain from the surface of the sensor. The principle behind mechanical energy harvesting is to convert the energy of the displacements and oscillations of a spring mounted mass component inside the harvester into electrical energy. Mechanical energy harvesting can be: Piezoelectric, electrostatic and electromagnetic.

Piezoelectric energy harvesting:

It is based on the piezoelectric effect for which mechanical energy from pressure, force or vibrations is transformed into electrical power by straining a piezoelectric material, In particular, strains in the piezoelectric material produce charge separation across the harvester, creating an electric field, and hence voltage, proportional to the stress generated. Voltage varies depending on the strain and time, and an irregular AC signal is produced. Piezoelectric energy conversion has the advantage that it generates the desired voltage directly, without need for a separate voltage source. However, piezoelectric materials are breakable and can suffer from charge leakage.

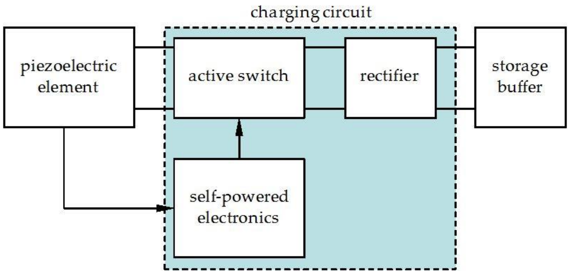

Figure 2: Piezoelectric Energy harvesting

Electrostatic energy harvesting:

The principle of electrostatic energy harvesting is based on changing the capacitance of a vibration dependent variable capacitor. In order to harvest the mechanical energy a variable capacitor is created by opposing two plates, one fixed and one moving, and is initially charged. When vibrations separate the plates, mechanical energy is transformed into electrical energy from the capacitance change. This kind of harvesters can be incorporated into microelectronic-devices due to their integrated circuit compatible nature [7]. However, an additional voltage source is required to initially charge the capacitor. Recent efforts to prototype sensor-size electrostatic energy harvesters can be found in.

Electromagnetic energy harvesting:

Electromagnetic energy harvesting is based on Faraday's law of electromagnetic induction. An electromagnetic harvester uses an inductive spring mass system for converting mechanical energy to electrical. It induces voltage by moving a mass of magnetic material through a magnetic field created by a stationary magnet. Specifically, vibration of the magnet attached to the spring inside a coil changes the flux and produces an induced voltage. The advantages of this method include the absence of mechanical contact between parts and of a separate voltage source, which improves the reliability and reduce the mechanical damping in this type of harvesters. However, it is difficult to integrate them in sensor nodes because of the large size of electromagnetic materials. Some examples of electromagnetic energy harvesting systems are presented in [8].

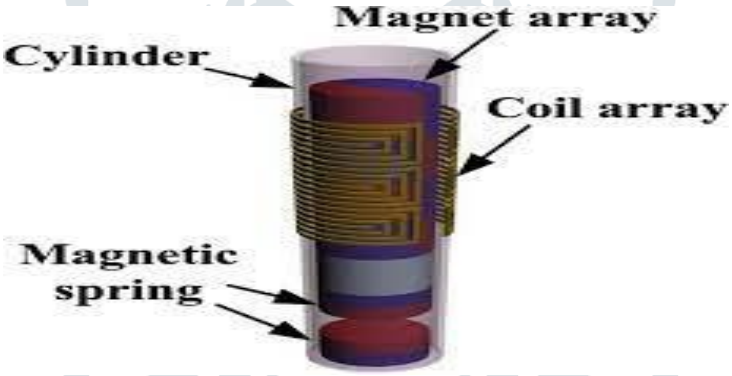

Figure 3: Electromagnetic Energy harvesting

Photovoltaic(solar) energy harvesting:

It is the process of converting incoming photons from sources such as solar or artificial light into electricity. Photovoltaic energy can be harnessed by using photovoltaic (PV) cells. These consist of two different types of semiconducting materials called n-type and p-type. An electrical field is formed in the area of contact between these two materials, called the P-N junction. Upon exposure to light a photovoltaic cell release electron. Photovoltaic energy conversion is a traditional, mature, and commercially established energy-harvesting technology. It provides higher power output levels compared to other energy harvesting techniques and is suitable for larger-scale energy harvesting systems. However, its generated power and the system efficiency strongly depend on the availability of light and on environmental conditions. Other factors, including the materials used for the photovoltaic cell, affect the efficiency and level of power produced by photovoltaic energy harvesters [7]. Known implementations of solar energy harvesting sensor nodes include Fleck [7], Enviromote [8] and Solar Biscuit [9].

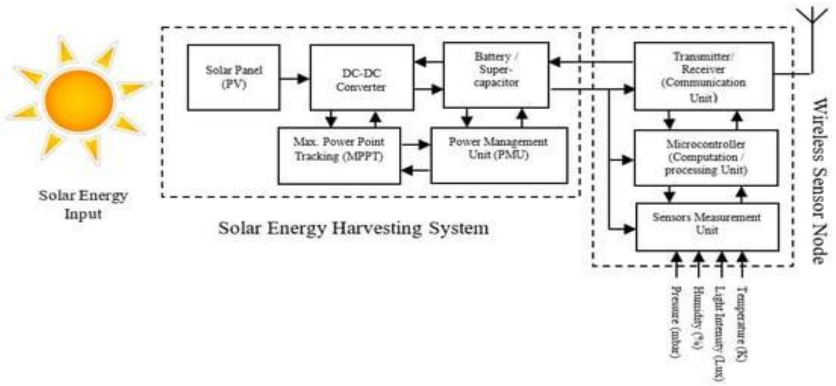

Figure 4: Solar Energy harvesting

Thermoelectric energy harvesting:

It is the process of creating electric energy from temperature difference (thermal gradients) using thermoelectric power generators (TEGs). The core element of a TEG is a thermopile formed by arrays of two dissimilar conductors, i.e., a p-type and n-type semiconductor (thermocouple), placed between a hot and a cold plate and connected in series. A thermoelectric harvester scavenges the energy based on the See beck effect, which states that electrical voltage is produced when two dissimilar metals joined at two junctions are kept at different temperatures. This is because the metals respond differently to the temperature difference, creating heat flow through the thermoelectric generator. This produces a voltage difference that is proportional to the temperature difference between the hot and cold plates. The thermal energy is converted into electrical power when a thermal gradient is created. Energy is harvested as long as the temperature difference is maintained.

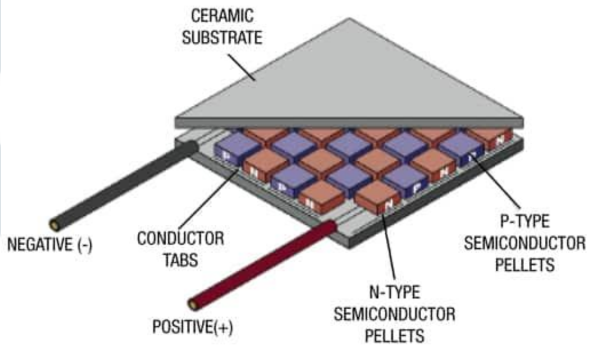

Figure 5: Thermoelectric energy harvesting

Pyroelectric energy harvesting:

It is the process of generating voltage by heating or cooling pyroelectric materials. These materials do not need a temperature gradient similar to a thermocouple. Instead, they need time-varying temperature changes. Changes in temperature modify the locations of the atoms in the crystal structure of the pyroelectric material, which produces voltage. To keep generating power, the whole crystal should be continuously subject to temperature change. Otherwise, the produced pyroelectric voltage gradually disappears due to leakage current. Pyroelectric energy harvesting achieves greater efficiency compared to thermoelectric harvesting. It supports harvesting from high temperature sources, and is much easier to get to work using limited surface heat exchange. On the other hand, thermoelectric energy harvesting provides higher harvested energy levels. Because of the various sizes of thermal harvesters, they can be placed on the human body, on structures and equipment.

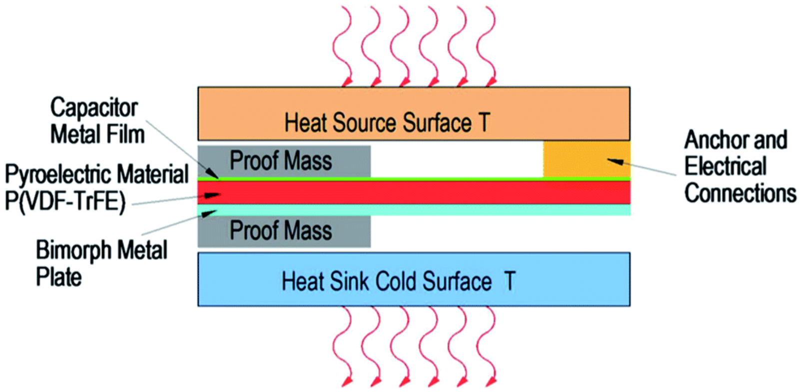

Figure 6: Pyroelectric Energy harvesting

Wireless energy harvesting:

It is the process of converting electromagnetic waves into electricity by a rectifying antenna, or rectenna. Energy can be harvested from either ambient RF power from sources such as radio and television broadcasting, cell phones, WiFi communications and microwaves, or from EM signals generated at a specific wavelength. Although there is a large number of potential ambient RF power, the energy of existing EM waves is extremely low because energy rapidly decreases as the signal spreads farther from the source. Therefore, in order to scavenge RF energy efficiently from existing ambient waves, the harvester must remain close to the RF source. Another possible solution is to use a dedicated RF transmitter to generate more powerful EM signals merely for the purpose of powering sensor nodes. Such RF energy harvesting is able to efficiently delivers powers from micro-watts to few milliwatts, depending on the distance between the RF transmitter and the harvester.

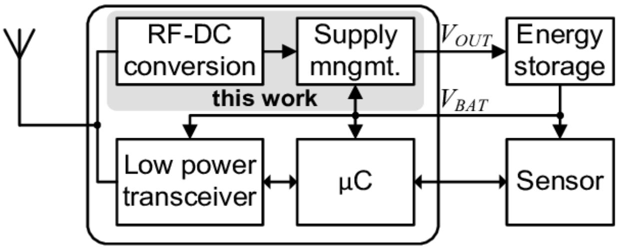

Figure 7: RF Energy harvesting techniques

Wind energy harvesting:

It is the process of converting air flow (e.g., wind) energy into electrical energy. A properly sized wind turbine is used to exploit linear motion coming from wind for generating electrical energy. A miniature wind turbine exists that are capable of producing enough energy to power WSN nodes. However, efficient design of small-scale wind energy harvesting is still ongoing research, challenged by very low flow rates, fluctuations in wind strength, the unpredictability of flow sources, etc. Furthermore, even though the performance of large-scale wind turbines is highly efficient.

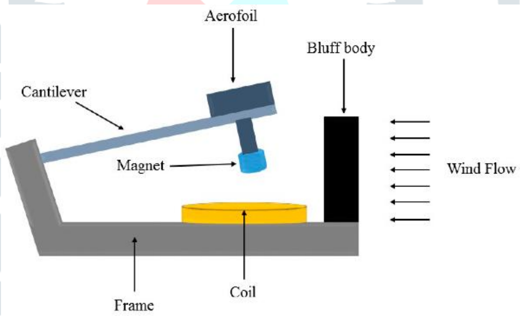

Figure 7: Wind Energy harvesting

Acoustic energy harvesting:

It is the process of converting high and continuous acoustic waves from the environment into electrical energy by using an acoustic transducer or resonator. The harvestable acoustic emissions can be in the form of longitudinal, transverse, bending, and hydrostatic waves ranging from very low to high frequencies. Typically, acoustic energy harvesting is used where local long term power is not available, as in the case of remote or isolated locations, or where cabling and electrical commutations are difficult to use such as inside sealed or rotating systems [10]. However, the efficiency of harvested acoustic power is low and such energy can only be harvested in very noisy environments. Harvestable energy from acoustic waves are much lower than what is achievable by other energy harvesting techniques.

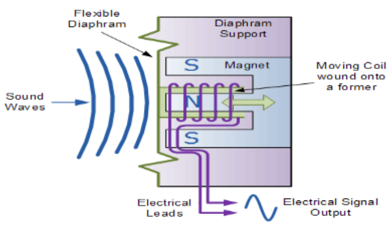

Figure 8: Acoustic Energy harvesting techniques

Hybrid energy harvesting:

All previously described harvesting techniques can be combined and concurrently used on a single platform (hybrid energy harvesting). the amount of energy harvestable from different sources is given in Table IV. For each energy harvesting technique we show its power density [10], The power density expresses the harvested energy per unit volume, area, or mass. Common unit measures of power density include watts per square centimetre and watts per cubic centimetre.

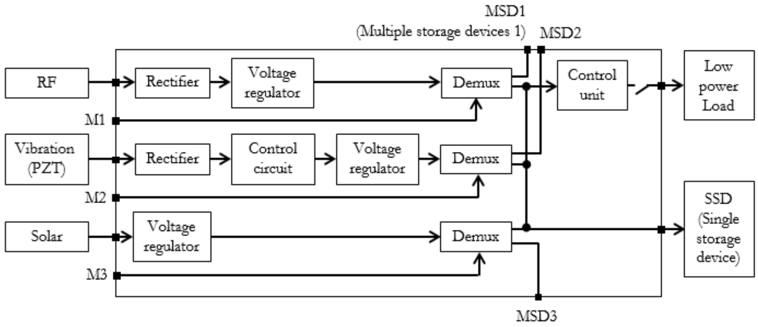

Figure 9: Hybrid Energy harvesting

Energy Source	Types	Energy-Harvesting Method	Power density
Radiant	Solar	Solar cells (indoors)	$<10\mu W/cm^2$
		Solar cells (outdoors, sunny days)	$15 mW/cm^2$
	RF	Electromagnetic conversion	$0.1\mu W/cm^2$ (GSM)
		Electromagnetic conversion	$0.01\mu W/cm^2$ (WiFi)
Mechanical	Wind Flow and Hydro	Electromechanical conversion	$16.2\mu W/cm^3$
	Acoustic Noise	Piezoelectric	$960 nW/cm^3$
	Motion	Piezoelectric	$330\mu W/cm^3$
Thermal	Body heat	Thermoelectric	$40\mu W/cm^2$

Table 1 : Energy-Harvesting Sources and their Corresponding Power Densities

IV. Energy-Harvesting Node Architecture:

Sensor nodes have evolved from large devices into current day small, embedded devices consisting of one or multiple sensing units, a radio transceiver, a processing unit, and a power unit (see Figure 10). Around 2010, sensor nodes with energy harvesters were introduced, which has led to the development of EH-WSNs. In these networks, the sensor node architecture is composed of one or multiple sensing units, a radio transceiver, a processing unit, an energy harvester, one or more energy storage units, a power management system, and possibly an energy predictor, as shown in Figure 10. The energy-harvesting system converts harvested energy into electrical energy for use by the sensor node, either directly (as shown in Figure 11(a)) or indirectly by first recharging the node energy storage (as shown in Figure 11(b)). In the latter, the energy storage is a basic part of the sensor node power unit that stores harvested energy and supplies the node with the required energy to operate. Furthermore, energy predictors are used to estimate the amount of harvested energy that will be available at any given time to a sensor node. Power management techniques have been a focal research point to achieve energy-neutral operation by using approaches like adaptive duty cycle Energy storage, energy prediction, and power management subsystems will be described in details in the following subsections

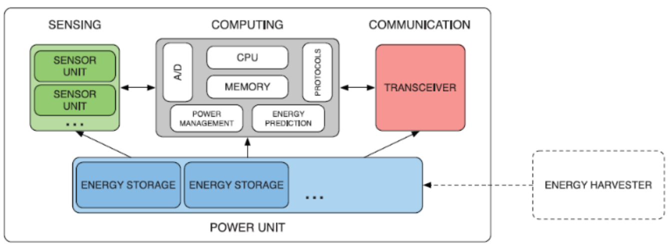

Figure 10: Wireless sensor node architecture

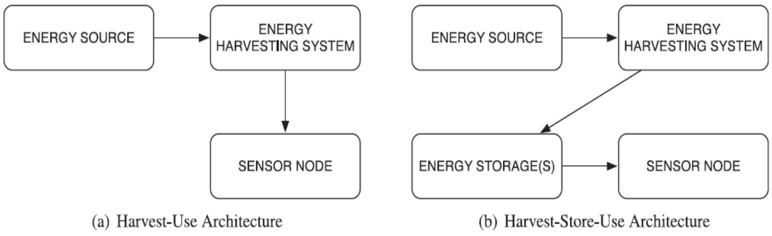

Figure 11: A sensor node architecture

V. Topologies of Energy Harvesting Systems

The ultimate goal of a typical wireless sensor node is to collect data of interest and infinitum. In order to operate indefinitely, a system cannot consume, on average, more power than a harvested source can provide. Otherwise, if the consumption exceeds the production, the system will eventually deplete its energy stockpile and stop working due to the empty energy reservoir and absence of environmental energy. This leads to undesirable system performance. [12] take a step further and present a theory of energy-neutral operation. Similar work has been presented in [13–16]. The main improvement is that the non-idealities of energy storage devices are considered, yielding a sounder theory. In [17], the sources and the consumers are modelled using the same mathematical model. This new model can also be considered as a generalization of [12]. Since the reasoning is similar for both theories, only the most relevant substance is presented here. There are three main topologies for energy harvesting systems: autonomous, hybrid autonomous, and battery-supplemented. Depending on the configuration, energy management strategies with different design goals are required [18].

Autonomous Harvesting Systems

Autonomous harvesting systems fully satisfy their energy needs from ambient sources, without batteries. Autonomous systems can only operate when the energy source is available, but their lifetime and performance are not limited by storage inefficiencies. These systems are inherently governed by the so-called energy neutrality principle, since they can never consume more energy than their harvesting device can deliver. To support these design goals, autonomous harvesting systems should employ prediction algorithms that give estimates of future available energy over time. A proper energy management strategy should allow such a system to achieve the desired utility within a variable energy environment [12]. The structure of an autonomous harvesting system is shown in Figure 12a. This is the simplest case, which consists of three major modules an energy harvesting module (HM), an energy converter module (CM), and an energy dissipation module (DM). The main disadvantage of this type of harvesting system is that if the load consumes less energy than what is available from the environment, the excess energy will be lost.

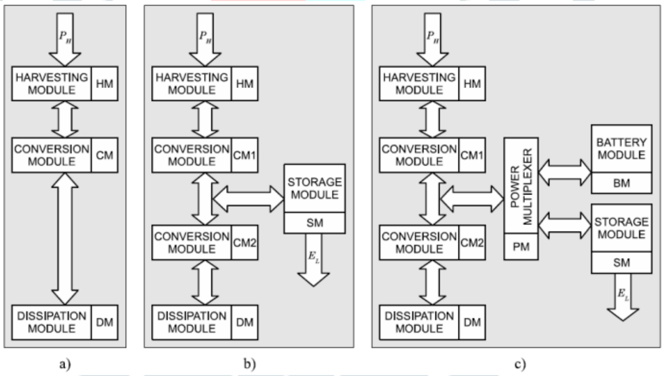

Figure 12. Topologies of harvesting systems: (**a**) autonomous harvesting system; (**b**) autonomous hybrid harvesting system; (**c**) battery-supplemented harvesting system (a, b, c)

Autonomous Hybrid Harvesting Systems

Autonomous hybrid harvesting systems are the most common type of energy harvesting system. They have an energy reservoir implemented using a secondary battery or ultracapacitor [19]. The harvesting device collects energy for system operation and the recharging of storage. This arrangement can dramatically increase the operational lifetime of the system. With proper energy management, this topology can achieve 0% dead time operation. The battery and the energy harvesting device must be sized so that they satisfy the energy needs of the system, possibly using the energy-neutrality principle [12]. The system can sometimes consume more energy than the harvesting source provides (using battery reserves), but the production/consumption rates have to be balanced over the long run. The structure of an autonomous hybrid harvesting system is shown in Figure 12b.

Battery-Supplemented Harvesting Systems

Battery-supplemented harvesting systems usually have a battery as the main source of energy and a harvesting device that plays an important, but secondary, role. The goal of energy management in such systems is to limit battery energy usage and to increase the system’s lifetime (e.g., by making external recharging or replacement of batteries less frequent). This system can use primary or secondary batteries. Harvested energy can directly or indirectly power the load or its specific parts. This approach greatly increases system reliability and allows data acquisition, processing, and transfer. As long as the primary batteries have some useful charge left, the system can continue to operate in situations when secondary storage is depleted and environmental energy is not available for harvest.

VI. Conclusions

Wireless sensor networks play a pivotal role in monitoring the environment. Over the years, energy management techniques have been shown to prolong the lifetime of sensor devices in monitoring the environment. This paper identifies and describes opportunities for future research in the area of wireless sensor networks (WSN)which are typically deployed in remote locations without the possibility of frequent maintenance. Additionally, the paper provides an overview of technologies that can be integrated to improve their reliability and operational efficiency. One of the research challenges from a single node perspective is selection of energy management-related parameters which have direct impact on the utilization of energy harvesting sources and energy storage. Their optimization would increase the system reliability. Since there is always a trade-off between environmental data measurement rate and data transmission rate, the application of advanced control algorithms, such as fuzzy logic controller or reinforcement learning , is an interesting research challenge and outlines one of the directions for future work. On the network level, one of the main incentives is to reduce the amount of data sent in both uplink and downlink directions via a network, which typically has some limitation in terms of data throughput per specific window of time. Therefore, the development of such solutions represents one of the most important research challenges. Yet another research challenge could be the development of methods for data processing and the prediction of operating parameters at the cloud level. This paper reviews current solutions and new trends in the area of energy harvesting sources and alternatives for energy storage, where one of the directions for further development might be using components that incorporate new materials, which could greatly increase their performance. My future work will focus on addressing the research challenges mentioned above so as to arrive at a better design, which will help to collect good-quality environmental data. In addition, discussed the unique features of EH-WSNs and their different energy prediction and management techniques, with a particular emphasis on their impact on the design of energy-harvesting-aware communication protocols.

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