Wireless Sensor Networks Powered by Ambient Energy Harvesting (WSN-HEAP) – Survey and Challenges

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Abstract—**Wireless sensor networks (WSNs) research has predominantly assumed the use of a portable and limited energy source, viz. batteries, to power sensors. Without energy, a sensor is essentially useless and cannot contribute to the utility of the network as a whole. Consequently, substantial research efforts have been spent on designing energy-efficient networking protocols to maximize the lifetime of WSNs. However, there are emerging WSN applications where sensors are required to operate for much longer durations (like years or even decades) after they are deployed. Examples include in-situ environmental/habitat monitoring and structural health monitoring of critical infrastructures and buildings, where batteries are hard (or impossible) to replace/recharge. Lately, an alternative to powering WSNs is being actively studied, which is to convert the ambient energy from the environment into electricity to power the sensor nodes. While renewable energy technology is not new (e.g., solar and wind) the systems in use are far too large for WSNs. Those small enough for use in wireless sensors are most likely able to provide only enough energy to power sensors sporadically and not continuously. Sensor nodes need to exploit the sporadic availability of energy to quickly sense and transmit the data. This paper surveys related research and discusses the challenges of designing networking protocols for such WSNs powered by ambient energy harvesting.**

I. INTRODUCTION

The greatest problem faced by wireless sensor networks is energy. When a sensor is depleted of energy, it can no longer fulfill its role unless the source of energy is replenished. Therefore, it is generally accepted that the usefulness of a wireless sensor expires when its battery runs out. Much of the research on wireless sensor networks has assumed the use of a portable and limited energy source, namely batteries, to power sensors and focused on extending the lifetime of the network by minimizing energy usage. Portable energy sources like batteries will experience current leakages that drain the resource even when they are not used; furthermore, any flaws in the packaging due to long term wear and tear can result in environmental problems. A wireless sensor network that is not dependent on a limited power source (like a battery) essentially has infinite lifetime. Failure due to other causes (like structural hardware damage) can be overcome by self-organization and network re-configuration. This has motivated the search for an alternative source of energy to power WSNs especially for applications that require sensors to be installed for long durations (up to decades) or embedded in structures where battery replacement is impractical. In this paper, we first provide a brief survey of research on energy harvesting wireless sensor networks. We then define the ideal WSN that is powered solely by energy harvesting which we refer to as *W*ireless *S*ensor *N*etwork *P*owered by *A*mbient *E*nergy *H*arvesting (WSN-HEAP) and then discuss the challenges in designing networking protocols for such WSNs arising from the characteristics of the energy source.

II. RESEARCH ON ENERGY HARVESTING

The use of renewable energy to generate electricity is not a new concept. Renewable energy that is being harvested to generate electricity today includes solar, wind, water and thermal energy. Harvesting energy for low-power (and possibly embedded) devices like wireless sensors presents a new challenge as the energy harvesting device has to be comparable in size (i.e. small enough) with the sensors. There are complex tradeoffs to be considered when designing energy harvesting circuits for WSNs arising from the interaction of various factors like the characteristics of the energy sources, energy storage device(s) used, power management functionality of the nodes and protocols, and the applications' requirements. Currently, the main sources of ambient energy considered suitable for use with WSNs are solar, mechanical (vibration or strain) and thermal energy. In the following subsections, we briefly survey research efforts in these areas.

A. Solar

Solar power is the most common and matured among the different forms of energy harvesting. However, it has the disadvantage of being able to generate energy only when there is sufficient sunlight or artifical light; furthermore, existing systems were not designed for use with low power WSNs, prompting new research efforts. With the envisioned indoor WSN applications, a system has been developed to address the needs of WSNs deployed in indoor environments (e.g. hospital and industrial) where lights are operational at close to 100% duty cycle [1]. To ensure that energy is not unnecessarily lost during the transfer from the harvester to the wireless sensor, a low-power maximum power point tracker (MPPT) circuit [2] has been proposed to efficiently transfer the harvested solar energy to rechargeable batteries even in non-optimal weather conditions. The Heliomote [3] project focused on developing a plug-and-play solar energy harvesting module for use with Crossbow/Berkeley motes. Another effort conducted empirical and mathematical analysis of two micro-solar power systems and used the results to propose design guidelines for micro-solar power systems for WSNs [4].

B. Mechanical

Vibrational, kinetic and mechanical energy generated by movements of objects can also be harvested. Vibrations are present all around us and especially prominent in bridges, roads and rail tracks. One method of harvesting vibrational energy is through the use of a piezoelectric capacitor while kinetic energy can be harvested using a spring-loaded mechanism. In [5], a vibration-based harvesting micro power generator is used to scavenge environmental vibrations for use in a sensor node. Traffic sensors can also be solely powered by the short duration vibrations when a vehicle passes over the sensor [6]. Experimental results have shown that when a piezoelectric pushbutton is depressed, sufficient energy is harvested to transmit two complete 12-bit digital word information wirelessly [7]. Similarly, a system that harvests energy from the forces exerted on a shoe during walking has been demonstrated [8] and indoor locations, like staircases, are potential locations to harvest vibrational energy for powering wireless environmental sensors, as shown in [9].

C. Thermal

Current is generated when there is a temperature difference between two junctions of a conducting material. Thermal energy harvesting uses temperature differences or gradients to generate electricity, e.g. between the human body and the surrounding environment. Devices with direct contact to the human body can harvest the energy radiated from the human body by means of thermogenerators (TEGs) [10]. To address the needs of telecommunications and other embedded applications, design of microstructured thermoelectric devices has been proposed in [11]. Due to the lack of moving parts in thermal energy harvesting devices, they tend to last longer than vibration-based devices.

D. Commercial Energy Harvesters

Energy harvesting devices are becoming available commercially. E.g., a Solar Energy Harvesting development kit, produced by Texas Instruments (http://www.ti.com), can be used to create perpetually powered wireless sensor networks based on their ultra-low power components. Advanced Cerametrics (http://www.advancedcerametrics.com) produces vibration-based energy harvesters that can replace batteries and be used to power wireless sensor nodes. Details on other commercially available energy harvesters for sensor nodes are available in [12].

III. RESEARCH IN ENERGY HARVESTING WSNS

While there has been extensive research on wireless sensor networks, those specific to energy harvesting WSNs are just emerging. With energy (or the lack of) being the key issue, it is unsurprising that the focus of research has been on power management.

A. Power Management

In this respect, most of the efforts have proposed the use of energy harvesting to supplement the on-board battery. Therefore, efficient power management is important to maximize the benefits of having the extra harvested energy. A consequence of using energy harvesting devices in sensor motes is that traditional metrics such as residual battery level is no longer usable in power management. Instead, information about future energy availability is required to make optimal routing decisions [13]. To achieve this, an environmental energy harvesting framework (EEHF) [14] has been proposed to adaptively learn the energy environment and make use of this information to more efficiently exploit the energy resources in order to improve the performance of the sensor network. A power management system, incorporating an analytical model for predicting various performance metrics, adaptive duty cycles and other related aspects, has also been developed [15]. Another approach assumes that sensors have two transmission modes that allow them to tradeoff energy consumption with packet error to maximize performance [16].

B. Data Delivery Schemes

Delivering data from a sensor across multiple wireless hops to the sink involves generally two key tasks: accessing the medium and forwarding the data to the next hop towards the sink. Energy conservation has been and remains as the key objective in the design of networking protocols for WSNs. A recent survey on WSN protocols can be found in [17]. Here, we focus our discussion specifically on works that are related to WSN-HEAP.

Many ultra-low power medium access control (MAC) protocols have been proposed for WSNs. However, any scheme that involves some form of backoff and retransmission is very likely to be non-optimal because timing schedules cannot be strictly enforced when a node has no energy to operate, and the amount of harvested energy may not be sufficient for retransmissions. A polling-based MAC protocol has been proposed for use in sensors powered by ambient vibrations but the scheme has not been shown to be optimal [18]. Cooperative transmission protocols, an active area of research in wireless communications, have also been proposed for use in energy harvesting wireless sensor nodes [19].

A straightforward approach to data forwarding involves modifying existing WSN routing protocols. Directed Diffusion, one of the early WSN routing protocols, has been modified to incorporate information on whether the node is running on solar or battery power [20], and the results have shown that the solar-aware variant performs better than shortest path routing. Similarly, a solar-cell energy model is incorporated into geographic routing to improve network performance. Since nodes may harvest different amounts of energy, their duty cycles may not be the same. In WSN-HEAP, maximizing the network throughput is the main consideration since energy can be replenished. However, the amount of power provided by the environment is limited, therefore we need to have a routing algorithm that takes into consideration actual environmental conditions [21]. The main idea is to model the network as a flow network and obtain the solution by solving the maxflow problem to maximize throughput. Another solution incorporates the energy replenishment rate into the cost metric when computing routes [22]. Geographic routing can also be modified to consider the amount of energy that can be harvested from the environment.

C. Topology and Connectivity

Power control is important to maintain connectivity through topology control. If the rate of harvested energy is not enough to power the sensor node continuously, this means that nodes have to go to sleep to charge up the battery, and this alters the network topology and therefore connectivity. The performance of different sleep and wakeup strategies based on factors such as channel state, battery state and environmental conditions are analyzed in [23] and game theory is also applied to find the optimal parameters for a sleep and wakeup strategy to tradeoff between packet blocking and dropping probabilities [24]. Another study presented an analytical framework [25] to estimate various statistical properties of the system (e.g. expected downtime) given specific system parameters, such as, energy harvesting rate, buffer capacity, etc. It has also been shown that clustering in sensor networks can be improved by considering the characteristics of the energy harvesting process [26].

D. Energy Storage Technology

Besides being difficult to replace in sensors embedded in structures such as buildings and bridges, batteries also have limited recharge cycles such that they cannot be further recharged beyond a threshold. For self-powered sensors with energy harvesting capabilities to be sustainable, an alternative form of energy storage is necessary – supercapacitors. Supercapacitors, which are recharged by energy harvesting devices, can replace batteries as the energy storage device. A supercapacitor can be recharged for more than half a million charge cycles and has a 10-year operational lifetime before the energy capacity is reduced to 80% [27]. The main difference between capacitors and supercapacitors lies in their energy storage density. Supercapacitors can store energy at higher energy density, and therefore its small form factor is more suitable for sensor nodes than using a capacitor.

E. State of Commercial Technology

Energy harvesting powered sensor nodes for specific applications, like indoor climatic monitoring and industrial environmental control, are commercially available. Battery-less sensor nodes that can be powered by any energy harvester are produced by Ambiosystems (http://www.ambiosystems.com). The sensor nodes developed by Microstrain (http://www.microstrain.com) harvest energy from two sources [28]; the first method uses tiny solar cells to convert solar energy while the second method uses piezoelectric materials to convert mechanical energy into electric energy. Another company, EnOcean (http://www.enocean.com), produces sensing systems that can power themselves by harvesting ambient energy from the environment.

IV. WSN-HEAP NODE CHARACTERISTICS

Using energy harvesting to supplement batteries does not eliminate the problem of having to replace the batteries when they run out. The process merely delays the inevitable. In applications like structural health monitoring of civil infrastructures, the sensors need to be installed in-situ (possibly embedded and out-of-reach after they are installed) and operate for long durations, from years to decades or even longer. Combining low-power electronics, energy harvesting devices, and supercapacitors, it is possible to implement WSNs that rely solely on energy harvesting to operate, i.e. WSN-HEAP.

Although WSN-HEAP is very promising for solving the energy constraints of traditional WSN, the power levels available from state-of-the-art energy harvesting devices is in the order of tens to thousands of μW or several mW (1% to 20% of operating power) which is not enough to power the sensor node continuously. Using the energy harvesting rates presented in [29], we estimate the duty cycle achievable by the Crossbow MICAz based on the power consumption requirements of 83.1mW in receive state and 76.2 mW in transmit state. We base our computation of the harvesting rate on a 10cm^2 material which is about the same size as the mote, and the results are shown in Table I.

TABLE I
ACHIEVABLE DUTY CYCLE BY MICAZ WITH 10CM^2 HARVESTING MATERIAL

Technology	Power Density [29] (μW/cm^2)	Energy Harvesting Rate (mW)	Duty Cycle (%)
Vibration - electromagnetic	4.0	0.04	0.05
Vibration - piezoelectric	500	5	6
Vibration - electrostatic	3.8	0.038	0.05
Thermoelectric	60	0.6	0.72
Solar - direct sunlight	3700	37	45
Solar - indoor	3.2	0.032	0.04

Without the sustained energy supply, the exact sleep and wakeup timings are unknown. Therefore, the operating characteristics of WSN-HEAP as compared to battery-operated WSN can be simply illustrated as shown in Figure 1. In WSN-

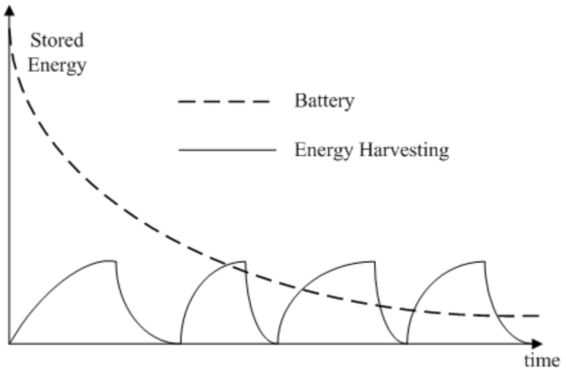

Fig. 1. WSN-HEAP vs Battery-powered WSN

HEAP, each sensor node is equipped with a small processor, a radio transceiver for communication, one or more energy harvesting devices, a capacitor/supercapacitor to store the harvested energy and a sensor. The key differentiating feature of a WSN-HEAP node (as compared to a battery-operated WSN node) is the energy source which is a combination of energy harvesting device (s) and supercapacitor(s) instead of batteries. The sink is powered by an external source and remains on all the time.

V. DESIGN CHALLENGES

Instead of focusing on energy-efficient networking protocols to maximize the lifetime of sensor networks, the main objective is to maximize the information or data collected from the sensor network given the rate of energy that can be harvested from the environment. In the following subsections, we briefly discuss the networking-related research issues.

A. *Topology Control*

Topology control schemes can exploit transmission power control to increase the probability of successfully delivering the data to the next hop [30]. Larger transmission power means that more energy is required to be harvested before the node can receive or transmit data packets, thereby decreasing the duty cycles of the node. This may be necessary if a node's neighbours have not harvested sufficient energy to operate. Therefore, transmission power control is crucial in optimizing the performance of WSN-HEAP. This also influences the logical topology and deployment strategies [31].

B. *MAC*

Typically, MAC protocols designed for WSNs aim to reduce energy usage and prolong network lifetime at the expense of longer delays. In the case of WSN-HEAP, it makes more sense to find a means of efficiently using the harvested energy to maximize throughput and minimize delays. Furthermore, unnecessary waiting (to synchronize with time slots) or retransmissions can be counter-productive; it has been shown in [32] that a slotted CSMA MAC performs worse than an unslotted scheme because energy is consumed during the slot synchronization process, resulting in longer harvesting periods thereby reducing throughput.

C. *Routing*

Since the wakeup time of any sensor cannot be estimated accurately because the exact rate of energy harvested fluctuates with time and other environmental factors, it is very difficult to ensure that the next-hop node is awake to receive a packet. The uncertainty in how long it takes a node to harvest enough energy before it can function again makes existing sleep-wake scheduling schemes for WSNs unusable since a node may not have harvested sufficient energy at the scheduled wake-up time. Furthermore, if it has depleted all its energy in its previous cycle, it may loose its timing reference when it wakes up again. Therefore, broadcast and opportunistic schemes are more suitable in WSN-HEAP. However, broadcasting may result in many duplicates if many nodes are awake; therefore, some form of duplication-suppression is needed so that the harvested energy is not wasted on delivering duplicates. The ideal situation would be anycast where exactly one node (among those awake and heard the packet transmission) will forward data packets towards the sink. This ensures that the sink receives exactly one copy of each packet from the source. If there are insufficient awake forwarding nodes, either because the density of the nodes deployed is too low or the average energy harvesting period is too long, then it becomes an intermittently connected mobile network, where the use of delay-tolerant network (DTN) techniques may be appropriate.

D. *Reliable Data Delivery*

Reliable data delivery may be required for some applications. Since the source node is not awake all the time, it is a challenge to design reliable transport protocols as many reliable transport protocols need to make use of positive feedback for retransmissions. Another requirement to ensure each flow gets its fair share of bandwidth given the amount of energy that can be harvested from the environment. Since energy is free because it is renewable, nodes further away from the sink may starve the nodes nearer the sink if forwarding packets have higher priority than the node's own packets. Therefore, there is a need for a transport protocol to regulate the data flow such that any source will get its fair share of bandwidth no matter where it is located in the network.

VI. CONCLUSION

Wireless sensor networks that are powered by ambient energy harvesting is a promising technology for many sensing applications as it eliminates the need to replace batteries. However, the current state of technology in energy harvesting is still unable to provide a sustained energy supply to enable WSNs continuously. Furthermore, the ability to harvest energy from the environment is highly dependent on many environmental factors and these need further research to understand and exploit. We have provided an overview of the research in WSNs powered by ambient energy harvesting and discussed the challenges in designing networking protocols for WSN-HEAP which are WSNs powered solely by energy harvesting. A comparative summary of the key aspects of WSN and WSN-HEAP is provided in Table II.

TABLE II
SUMMARY OF KEY ASPECTS OF WSN AND WSN-HEAP

	Battery-operated WSNs	Battery-operated WSNs with Energy Harvesters	WSN-HEAP
Goal	Throughput and latency are usually traded off for longer network lifetime	Longer lifetime achieved by supplementing battery power with harvested energy	Maximize throughput and minimize delay since energy is renewable & no concept of lifetime
Protocol Design	Sleep-and-wakeup schedules can be determined precisely	Sleep-and-wakeup schedules can be determined if future energy availability is correctly predicted	Sleep-and-wakeup schedules cannot be predicted
Energy Model	Energy model is well understood	Energy model can be predicted to high accuracy	Energy harvesting rate varies across time, space as well as type of energy harvester

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