Energy Harvesting Sensor Nodes: Survey and Implications

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***Abstract*—Sensor networks with battery-powered nodes can seldom simultaneously meet the design goals of lifetime, cost, sensing reliability and sensing and transmission coverage. *Energy-harvesting*, converting ambient energy to electrical energy, has emerged as an alternative to power sensor nodes. By exploiting recharge opportunities and tuning performance parameters based on current and expected energy levels, energy harvesting sensor nodes have the potential to address the conflicting design goals of lifetime and performance. This paper surveys various aspects of energy harvesting sensor systems—architecture, energy sources and storage technologies and examples of harvesting-based nodes and applications. The study also discusses the implications of recharge opportunities on sensor node operation and design of sensor network solutions.**

***Index Terms*—Sensor networks, Energy-aware systems, Energy harvesting.**

I. INTRODUCTION

A SENSOR network, a network of collaborating embedded devices (sensor nodes) with capabilities of sensing, computation and communication, is used to sense and collect data for application specific analysis. A sensor network application has several design dimensions, sensing modality, sensor node computation, communication and storage capabilities, cost and size of each node, type of power source, architecture for deployment, protocols for data dissemination and communication, applications and management tools, to name a few. A typical and widely deployed application category is one that uses battery-powered sensor nodes. A few instantiations of such applications are, *Habitat monitoring* [1], *Volcano monitoring* [2], *Structural monitoring* [3], [4] and *Vehicle tracking* [5]. Untethered sensor nodes used in these deployments facilitate mobility and deployment in hard-to-reach locations.

A major limitation of untethered nodes is finite battery capacity—nodes will operate for a finite duration, only as long as the battery lasts. Finite node lifetime implies finite lifetime of the applications or additional cost and complexity to regularly change batteries. Nodes could possibly use large batteries for longer lifetimes, but will have to deal with increased size, weight and cost. Nodes may also opt to use low-power hardware like a low-power processor and radio, at the cost of lesser computation ability and lower transmission ranges.

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Several solution techniques have been proposed to maximize the lifetime of battery-powered sensor nodes. Some of these include energy-aware MAC protocols (SMAC [6], BMAC [7], XMAC [8]), power aware storage, routing and data dissemination protocols [9], [10], [11], duty-cycling strategies [12], [13], adaptive sensing rate [14], tiered system architectures [15], [16], [17] and redundant placement of nodes [18], [19]. While all the above techniques optimize and adapt energy usage to maximize the lifetime of a sensor node, the lifetime remains bounded and finite. The above techniques help prolong the application lifetime and/or the time interval between battery replacements but do not preclude energy-related inhibitions. With a finite energy source, seldom can all the performance parameters be optimized simultaneously, e.g., higher battery capacity implies increased cost, low duty-cycle implies decreased sensing reliability, higher transmission range implies higher power requirement and lower transmission range implies transmission paths with more number of hops resulting in energy usage at more number of nodes.

An alternative technique that has been applied to address the problem of finite node lifetime is the use of *energy harvesting*. Energy harvesting refers to harnessing energy from the environment or other energy sources (body heat, foot strike, finger strokes) and converting it to electrical energy. The harnessed electrical energy powers the sensor nodes. If the harvested energy source is large and periodically/continuously available, a sensor node can be powered perpetually. Further, based on the periodicity and magnitude of harvestable energy, system parameters of a node can be tuned to increase node and network performance. Since a node is energy-limited only till the next harvesting opportunity (recharge cycle), it can optimize its energy usage to maximize performance during that interval. For example, a node can increase its sampling frequency or its duty-cycle to increase sensing reliability, or increase transmission power to decrease length of routing paths.

As a result, energy harvesting techniques have the potential to address the tradeoff between performance parameters and lifetime of sensor nodes. The challenge lies in estimating the periodicity and magnitude of the harvestable source and deciding which parameters to tune and simultaneously avoid premature energy depletion before the next recharge cycle.

As part of this study, we present details of energy harvesting techniques—architectures, energy sources, storage technologies and examples of applications and network deployments. Further, as mentioned above, sensor nodes can exploit energy harvesting opportunities to dynamically tune system parameters. These adaptations have interesting implications on the design of sensor network applications and solutions, which we discuss. As contributions of this study we present and discuss,

- basics of energy harvesting techniques,
- details of energy sources used for harvesting and corresponding energy storage technologies,
- energy harvesting architectures,
- examples of energy harvesting systems and applications based on these systems and
- implications of energy harvesting on design of sensor network applications and solutions.

The rest of the paper is organized as follows, Section II describes basic concepts, components and types of energy harvesting nodes. Examples of energy harvesting sensor nodes and related applications are presented in Section III. Section IV presents implications of harvestable energy on sensor network applications and solutions design. Section V concludes the paper.

II. Energy Harvesting Sensor Nodes

Energy harvesting refers to scavenging energy or converting energy from one form to the other. Applied to sensor nodes, energy from external sources can be harvested to power the nodes and in turn, increase their lifetime and capability. Given the energy-usage profile of a node, energy harvesting techniques could meet partial or all of its energy needs. A widespread and popular technique of energy harvesting is converting solar energy to electrical energy. Solar energy is uncontrollable—the intensity of direct sunlight cannot be controlled—but it is a predictable energy source with daily and seasonal patterns. Other techniques of energy harvesting convert mechanical energy or wind energy to electrical energy. For example, mechanical stress applied to piezo-electric materials, or to a rotating arm connected to a generator, can produce electrical energy. Since the amount of energy used for conversion can be varied, such techniques can be viewed as controllable energy sources.

A typical energy harvesting system has three components, the Energy source, the Harvesting architecture and the Load. *Energy source* refers to the ambient source of energy to be harvested. *Harvesting architecture* consists of mechanisms to harness and convert the input ambient energy to electrical energy. *Load* refers to the activity that consumes energy and acts as a sink for the harvested energy.

A. Energy Harvesting Architectures

Broadly, energy harvesting can be divided into two architectures— (i) *Harvest-Use*: Energy is harvested just-in-time for use and (ii) *Harvest-Store-Use*: Energy is harvested whenever possible and stored for future use. A similar categorization is present in [20].

1) Harvest-Use Architecture: Figure 1(a) shows the *Harvest-Use* architecture. In this case, the harvesting system directly powers the sensor node and as a result, for the node to be operational, the power output of the harvesting system has to be continuously above the minimum operating point. If sufficient energy is not available, the node will be disabled. Abrupt variations in harvesting capacity close to the minimum power point will cause the sensor node to oscillate in ON and OFF states.

A *Harvest-Use* system can be built to use mechanical energy sources like pushing keys/buttons, walking, pedaling, etc. For example, the push of a key/button can be used to deform a piezo-electric material, thereby generating electrical energy to send a short wireless message[21]. Similarly, piezo-electric materials strategically placed within a shoe may deform to different extents while walking and running. The harvested energy can be used to transmit RFID signals, used to track the shoe-wearer[22], [23], [24].

2) Harvest-Store-Use Architecture: Figure 1(b) depicts the *Harvest-Store-Use* architecture. The architecture consists of a storage component that stores harvested energy and also powers the sensor node. Energy storage is useful when the harvested energy available is more than its current usage. Alternatively, energy can also be hoarded in storage until enough has been collected for system operation. Energy is stored to be used later when either harvesting opportunity does not exist or energy usage of the sensor node has to be increased to improve capability and performance parameters. The storage component itself may be single-stage or double-stage. *Secondary storage* is a backup storage for situations when the *Primary storage* is exhausted[25].

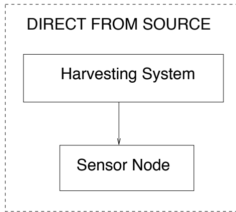
As an example, a *Harvest-Store-Use* system can use uncontrolled but predictable energy sources like solar energy[25], [26], [27], [28]. During the daytime, energy is used for work and also stored for later use. During night, the stored energy is conservatively used to power the sensor node.

B. Sources of Harvestable Energy

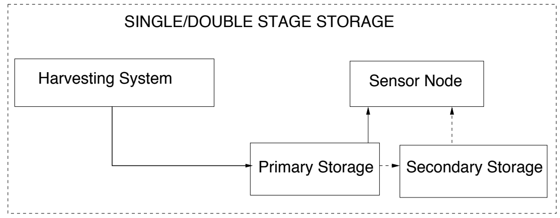
A vital component of any energy harvesting architecture is the energy source—it dictates the amount and rate of energy available for use. Energy sources have different characteristics along the axes of controllability, predictability and magnitude[20]. A *controllable* energy source can provide harvestable energy whenever required, energy availability need not be predicted before harvesting. With *non-controllable* energy sources, energy must be simply harvested whenever available. In this case, if the energy source is predictable then a prediction model which forecasts its availability can be used to indicate the time of next recharge cycle. Further, energy sources can be broadly classified into the following two categories, (i) *Ambient Energy Sources*: Sources of energy from the surrounding environment, e.g., solar energy, wind energy and RF energy, and (ii) *Human Power*: Energy harvested from body movements of humans [21], [22], [23], [24]. Passive human power sources are those which are not user controllable. Some examples are blood pressure, body heat and breath[24]. Active human power sources are those that are under user control, and the user exerts a specific force to generate the energy for harvesting, e.g., finger motion, paddling and walking[24].

C. Energy Conversion Mechanisms

This refers to mechanisms for scavenging electrical energy from a given energy source. The choice of energy conversion mechanism is closely tied to the choice of energy source. In



(a) Harvest-Use



(b) Harvest-Store-Use

Fig. 1. Energy harvesting architectures with and without storage capability.

TABLE I
LISTING AND CHARACTERIZATION OF ENERGY SOURCES.

Energy Source	**Characteristics**	**Amount of Energy Available**	**Harvesting Technology**	**Conversion Efficiency**	**Amount of Energy Harvested**
Solar[25], [26], [27], [28]	Ambient, Uncontrollable, Predictable	$100mW/cm^2$	Solar Cells	15%	$15mW/cm^2$
Wind[28]	Ambient, Uncontrollable, Predictable	-	Anemometer	-	1200mWh/day
Finger motion[22], [24]	Active human power, Fully controllable	19mW	Piezoelectric	11%	2.1mW
Footfalls[22], [24]	Active human power, Fully controllable	67W	Piezoelectric	7.5%	5W
Vibrations in indoor environments[29]	Ambient, Uncontrollable, Unpredictable	-	Electromagnetic Induction	-	$0.2mW/cm^2$
Exhalation[24]	Passive human power, Uncontrollable, Unpredictable	1W	Breath masks	40%	0.4W
Breathing[24]	Passive human power, Uncontrollable, Unpredictable	0.83W	Ratchet-flywheel	50%	0.42W
Blood Pressure[24]	Passive human power, Uncontrollable, Unpredictable	0.93W	Micro-generator	40%	0.37W

TABLE II
COMPARISON OF RECHARGEABLE BATTERY TECHNOLOGIES [26].

Battery Type	**Nominal Voltage (V)**	**Capacity (mAh)**	**Weight Energy Density (Wh/kg)**	**Power Density (W/kg)**	**Efficiency (%)**	**Self Discharge (%/month)**	**Memory Effect?**	**Charging Method**	**Recharge Cycles**
SLA	6	1300	26	180	70-92	20	No	Trickle	500-800
NiCd	1.2	1100	42	150	70-90	10	Yes	Trickle	1500
NiMH	1.2	2500	100	250-1000	66	20	No	Trickle	1000
Li-ion	3.7	740	165	1800	99.9	<10	No	Pulse	1200
Li-polymer	3.7	930	156	3000	99.8	<10	No	Pulse	500-1000

case of solar energy, the conversion mechanism is the use of solar panels. A solar panel acts like a current source and the amount of current generated is directly proportional to its size/area and intensity of incident light. Hence, depending upon the requirements, bigger panels with larger area or more number of solar panels are employed. In case of mechanical sources of energy like walking, paddling, pushing buttons/keys, the conversion to electrical energy is done using piezo-electric elements[21], [22], [23], [24]. Piezo-electric films and ceramics deform upon application of force and generate electric energy. Larger the size of the film, larger is the amount of energy harvested. Wind energy is harvested using rotors and turbines that convert circular motion into electrical energy by the principle of electromagnetic induction[28], [30]. Section III presents details of various energy sources and systems that use these energy sources.

Table I tabulates characteristics of different energy sources as *fully controllable, partially controllable, uncontrollable but predictable* and *uncontrollable and unpredictable*. It also lists, for each energy source, the amount of energy available, the conversion/harvesting technology, the conversion efficiency and the amount of energy thus harvestable. Solar energy is the most easily accessible/available energy source and can provide $15mW/cm^2$ [31], [32]. It is uncontrollable but predictable—daily and seasonal, sunrise and sunset timings can be fairly accurately estimated. Solar energy is freely available and solar panels are small enough to fit the form factor of wireless sensor nodes also. This makes solar the most promising among the harvestable energy sources.

Wind energy is another example of an uncontrollable but predictable energy source. Though wind energy is also freely available and holds much promise as an alternative power source ($1200mWh/day$), the turbines and wind generators are bulkier than desirable. Pushing a button to cause vibration of piezo-electric material[21], and thus generating energy is an example of a controllable source. Here, the button can be pushed at will, to generate energy. Such active human power sources like finger motion and footfalls are useful to power small electronic devices but their use would be restricted to domestic/local uses and may not apply to remote wireless sensor network deployments. Similarly, passive human power sources like body heat, exhalation, breathing and blood pressure give sizeable amounts of power in the order of a few hundred mW, but they can be inconvenient and burdensome to the human body.

No single energy source is ideal for all applications. The choice depends on every application's requirements and constraints. In the following sections, we will see different sensor node prototypes that harvest energy from sources like solar, finger motion and footfalls.

D. Storage Technologies

Storage technology plays an important role in energy harvesting systems and, as a consequence, the choice of the storage component and recharge technology is of prime significance. Rechargeable batteries, a common choice of energy storage, can be made up of any one of several technologies (chemical compositions). A rechargeable battery is a storage cell that can be charged by reversing the internal chemical reaction. A few popular rechargeable technologies are Sealed Lead Acid (SLA), Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH) and Lithium Ion (Li-ion). These battery technologies can be characterized along several axes — energy density, power density, charge-discharge efficiency[1], self-discharge rate and number of deep recharge cycles[2].

Table II shows typical values of the above parameters across different battery technologies. Nominal voltages for SLA, NiCd, NiMH and Li-ion batteries are 6 volts, 1.2 volts, 1.2 volts and 3.7 volts, respectively. Table II shows that Lithium ion batteries have highest output voltage, energy density, power density and charge-discharge efficiency. They also have low self-discharge rate[3]. Though NiMH batteries have better energy density and power density than NiCd batteries, NiCd batteries have higher number of deep recharge cycles. Sealed Lead Acid batteries have the lowest values for energy density, power and number of cycles and hence is the least effective storage technology.

Two storage technologies, NiMH and Li-based, emerge as good choices for energy harvesting nodes. Lithium batteries have high output voltage, energy density, efficiency and moderately low self-discharge rate. They do not suffer from *memory effect*—loss of energy capacity due to repeated shallow recharge[4]. However, Lithium batteries require *pulse-charging* for recharge—a high pulsating charging current. Usually an auxiliary battery or a charging circuit is required for this purpose. On the other hand, NiMH batteries can be *trickle* charged, i.e., directly connected to an energy source for charging, and do not need complex pulse charging circuits. They have reasonably high energy, power density and number of recharge cycles. Though NiMH batteries do suffer from memory effect, the effect is reversible by conditioning—fully discharging the battery after charging it. Additionally, the charge-discharge efficiency of NiMH batteries is lower than Lithium-based batteries. As can be seen, both storage technologies have pros and cons and the choice depends on the tradeoff dictated by the application requirements and constraints. In the following sections, we will present examples of prototype nodes that use both NiMH and Lithium batteries for different requirements and deployment conditions.

Alternatively, super-capacitors can be used as storage components instead of, or along with, rechargeable batteries. Like batteries, super-capacitors also store charge, but they self-discharge at a much higher rate than batteries, as much as 5.9% per day[26]. Additionally, a super-capacitor's weight-to-energy density is very low, only 5Wh/kg as compared to 100Wh/kg of NiMH batteries. However, super-capacitors have high charge-discharge efficiency ($97-98\%$) and also do not suffer from memory effect. Super-capacitors can also be trickle-charged like NiMH batteries and hence do not need complex charging circuitry. Theoretically, super-capacitors have infinite recharge cycles, and therefore have no limit to the number of times they can undergo deep recharge[25]. Thus, super-capacitors are useful storage elements in locations where ample energy is available at regular intervals. They can also be used to buffer the available energy if the energy source is jittery, i.e., the super-capacitor is trickle charged and a stable discharge from the capacitor charges the battery.

III. Energy Harvesting Sensor Nodes and Applications

This section describes implementations of energy harvesting sensor nodes and applications designed to use various energy sources such as solar energy [20], [25], [27], [28], [33], [34], [35], active user power [21], [22], [23], [24], [36], wind energy [28], [30] and RF energy [37], [38], [39], [40], [41], [42].

A. Solar Energy Harvesting Systems

Since solar energy is easily available and is a convenient harvesting source, several implementations of solar energy harvesting sensor nodes exist. Prometheus[25], HydroWatch[26], Heliomote[27], Ambimax[28], Everlast[34] and Sunflower[35] are different types of solar harvesting sensor nodes described in this section. These solar energy harvesting implementations are different along the axes of characteristics of solar panels, battery type and capacity, and complexity of recharge circuit. Further, all these nodes use the *Harvest-Store-Use* architecture and use different options for storage—battery, super-capacitors or both (*tiered storage*).

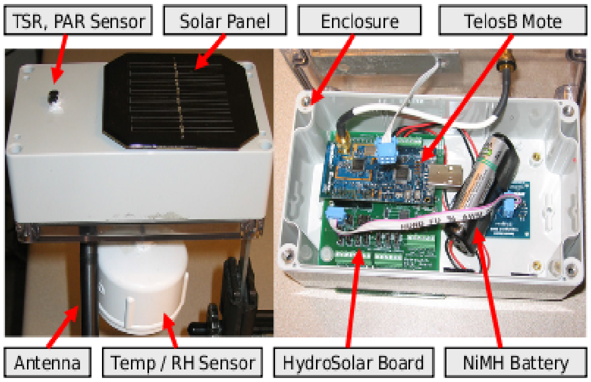
1) Nodes with Battery-based Storage: The *HydroWatch* node[26] is a single-storage energy harvesting system for scavenging solar energy, which uses the TelosB[43] platform

[1] Charge-discharge efficiency is the ratio of energy stored into the battery to the energy delivered to the battery

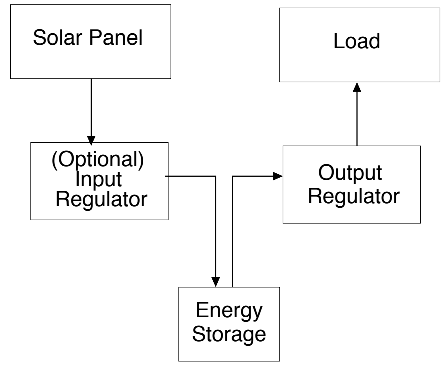
[2] Deep recharge cycle refers to the cycle of recharging the battery after a complete drain-out

[3] Self-discharge is the loss of battery capacity while it simply sits on the shelf.

[4] Shallow recharge refers to recharging a partially discharged battery.



(a) HydroWatch weather node.



(b) HydroWatch power subsystem architecture.

Fig. 2. HydroWatch weather node and its power subsystem architecture [26].

with NiMH batteries. Figure 2 shows the HydroWatch node and the system architecture of its micro-solar power subsystem. The HydroWatch node uses a solar panel of area 2.3 inches x 2.3 inches which outputs 276mW at a voltage of 3.11V. The solar panel power is used to recharge two NiMH battery of 2500mAh capacity each. An input regulator is used to match the current limit, voltage limit and charging duration of the battery. However, due to usage of NiMH batteries that can be trickle charged, limiting the charging duration is not necessary. Therefore, if it can be ensured that the operating voltage of the solar panel matches the charging voltage of the batteries, then the input regulator becomes an optional component in the design. In fact, since the input regulator is observed to have 50% efficiency [26], its removal increases the energy efficiency of the HydroWatch node quite significantly. An output regulator is used to match the battery voltage to the mote requirements.

HydroWatch uses NiMH batteries, preferred over Li-ion batteries. Integrating a hardware Li-ion charger is complex compared to the straight-forward charging logic of the NiMH batteries. The drawback of using NiMH is the high self-discharge rate of 30% and the low input-output efficiency of 66%, but the developers tradeoff this drawback for the simple charging logic. With 30 minutes of sunlight, the NiMH batteries receive more than 120mWh/day (79.2mWh/day at 66% efficiency), enough to fulfill application requirements.

Hydrowatch was evaluated using two network deployments, one in an urban environment and the other in a forest watershed. In the urban environment, all nodes received at least half an hour of sunlight (>130mWh) everyday. Interestingly, it was also observed that normally-occluded solar panels received more solar energy on cloudier days than sunny days. This was attributed to the diffusion of light caused by the cloud layers. However, in the forest watershed, most of the nodes did not receive more than $50mWh$ of energy a day which was less than the targeted 79.2mWh/day. This scarcity of energy was not because of unavailability of sunlight, but because of the spotted light, whose dot sizes were not large enough to cover an entire solar panel. Such a panel which received partial lighting, also limited the current flow through the other panels connected in series with it. Many small panels connected in a highly parallel configuration, causing additive increase in current flow, maybe more appropriate in such conditions.

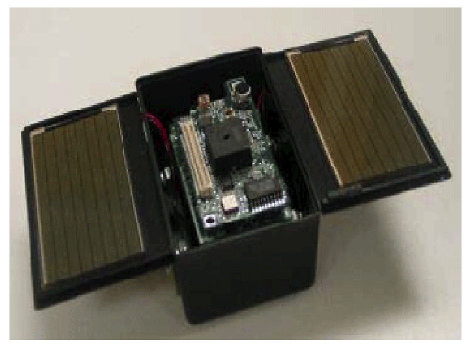


Fig. 3. The Heliomote prototype node[27].

Heliomote[27] is also a single-storage energy harvesting system using NiMH batteries. The architecture of Heliomote is similar to that of HydroWatch. However, unlike HydroWatch, it is built using the Mica2 platform [44], [45]. Figure 3 shows a picture of the Heliomote prototype. Heliomote uses a solar panel with dimensions 3.75 inches x 2.5 inches, which outputs 198mW at a voltage of 3.3V. Though Heliomote has similar design as HydroWatch, Heliomote was designed as a plug-and-play enhancement for Crossbow motes. Hence, unlike HydroWatch, the DC/DC converter (output regulator) is not exactly matched to the battery and the load. This makes the under-charge protection element mandatory for Heliomote, because continuing to draw power even after the battery voltage has dropped below a low threshold can cause damage to the rechargeable batteries. Also, Heliomote uses an over-charge protection unit to prevent instability due to over-charging. Such protection had been unwarranted in HydroWatch design due to the fact that in the targeted watershed environment, energy availability itself was very less.

Heliomote also has an energy monitoring component which enables a sensor node to learn its energy availability and usage. The Energy Monitor component of the Heliomote measures and conveys information regarding the magnitude and variance of energy available in battery. Information from the energy monitoring component can be used by the micro-controller to

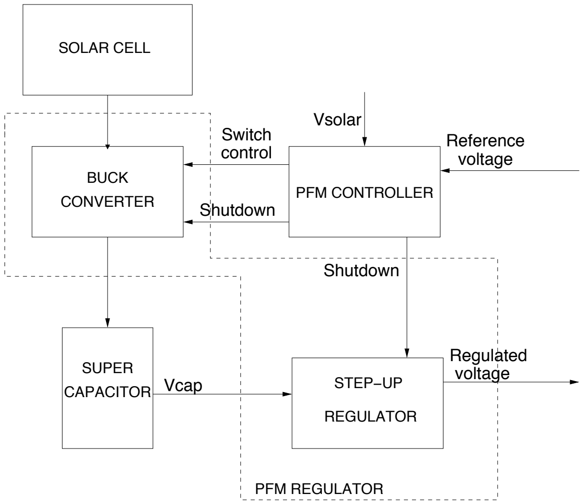


Fig. 4. Block diagram of Everlast's energy harvesting subsystem[34].

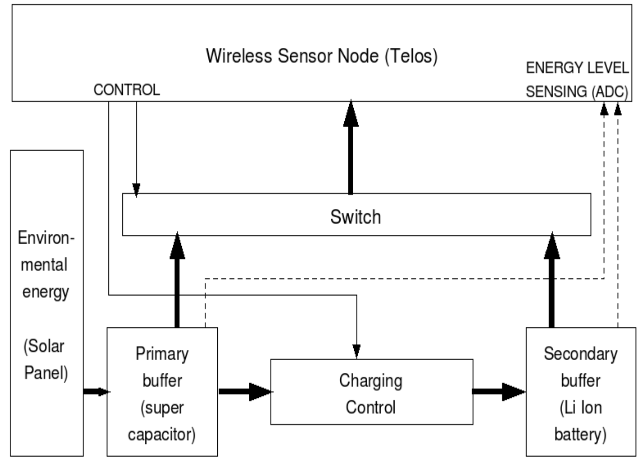


Fig. 5. Prometheus energy harvesting architecture [25].

perform harvesting-aware performance adaptation. An analysis of the heliomote harvesting architecture shows that if the battery size is enough to accommodate the variability in harvested energy and the rate of consumption of power is less than the rate of sourced power, then perpetual operation can be achieved. A thorough and complete mathematical analysis of these conditions is presented in [20]. Section IV discusses in more detail, the implications of energy harvesting on wireless sensor node applications.

Fleck1[46] is also a single-stage-storage solar energy harvesting system using NiMH batteries. Fleck1 is an integrated node and uses an ATmega128[47] processor and Nordic nRF903 radio chip[48] (operating at 433MHz). The solar panel measures $100cm^2$ and outputs 2100mWh/day. Experiments with Fleck1 showed that using a DC-DC converter or regulator to power the node from the battery is useful because it allows the node to be powered for longer, powering the circuit even at low voltage like 1.2V. This is especially useful if the node is batteryless, i.e., uses super-capacitors instead of batteries.

2) Nodes with Supercapacitor-based Storage: Everlast[34] is a supercapacitor-operated wireless sensor node and does not use batteries for energy storage. It attempts to break the performance-lifetime trade off by using a $100F$ super-capacitor having $300J$ energy storage, a low supply current MCU (PIC16LF747[49] - from 25μA at 31.25kHz to 930μA at 8MHz) and a low power transceiver supporting 1Mbps data stream (Nordic nRF2401[50] - 0dBm power, typically 13mA supply current at 3V). Everlast is an integrated system with sensors, radio, micro-controller and the energy harvesting subsystem, unlike Heliomote and HydroWatch, which are add-ons for existing platforms. Figure 4 shows the block diagram of the energy harvesting sub-system of Everlast.

As shown in Figure 4, the components of Everlast's energy scavenging subsystem are: a solar cell, a super-capacitor, PFM controller and PFM regulator. Everlast uses a pulse frequency modulated (PFM) regulator to charge the super-capacitor. The function of the PFM regulator is to charge a capacitor and then transfer the energy to the output load super-capacitor. The PFM regulator consists of a buck converter and a step-up regulator. Connecting a super-capacitor directly to the solar panel results in the solar voltage falling to the super-capacitor voltage, instead of the super-capacitor charging up. So a switched-capacitor circuit (with a smaller capacitor of 1μF) and buck converter is used to efficiently charge the load super-capacitor of 100F. When the solar voltage exceeds the specified reference V_{MPP}[5], the PFM controller (comparator) pulses the PFM regulator, denoted as "Switch control" signal in Figure 4. This causes flow of charge from input capacitor into the buck converter's inductor and into the load super-capacitor, thus charging it. Once the super-capacitor is fully charged, the PFM controller shuts down the PFM regulator by comparing its voltage to a 2.5V reference voltage and sending the "Shutdown" signal. Using this technique, Everlast claims a lifetime of 20 years at 50% duty cycle and 1Mbps data rate.

Solar-Biscuit[51] is another example of a solar-energy harvesting node using super-capacitors. It is an integrated node and uses the PIC 18LF452 microchip[52] and a Chipcon CC1000 radio[53]. A 5V, 1F super-capacitor is directly connected to the 5cm $\times$ 5cm solar-panel. Unlike Everlast, Solar-Biscuit has no regulation of voltage on input or output sides of the (super-capacitor) storage.

Sunflower[35] is another implementation of a solar energy harvesting node that uses super-capacitors. It uses four PIN photo diodes, a miniature super-capacitor (0.2F) and has a form-factor of 0.9 inch $\times$ 1.2 inch. It uses a MSP430F1232 microcontroller[54] which has a power draw of 540μW when active, at a operating voltage of 2.7V. Similar to Everlast, Sunflower employs a switching regulator to charge the super-capacitor from the photo diodes.

3) Nodes with Tiered Storage: Prometheus [25] is a double-storage energy harvesting system for scavenging solar energy using the TelosB platform[43], [45]. It uses two $22F$ super-capacitors in series as primary storage and a $200mAh$ Lithium polymer battery as the secondary storage. A solar panel measuring 3.23in $\times$ 1.45in with a power output of 130mW, is used to charge the super-capacitors. During times of excess

[5]MPP (Maximal Power Point) is the voltage and current combination that maximizes power output under given sunlight and temperature conditions and V_{MPP} is the voltage at MPP.

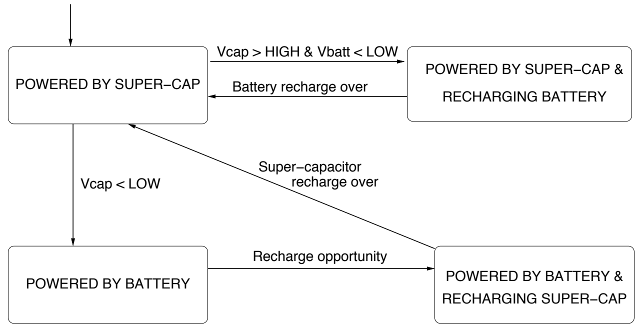


Fig. 6. State diagram of Prometheus driver.

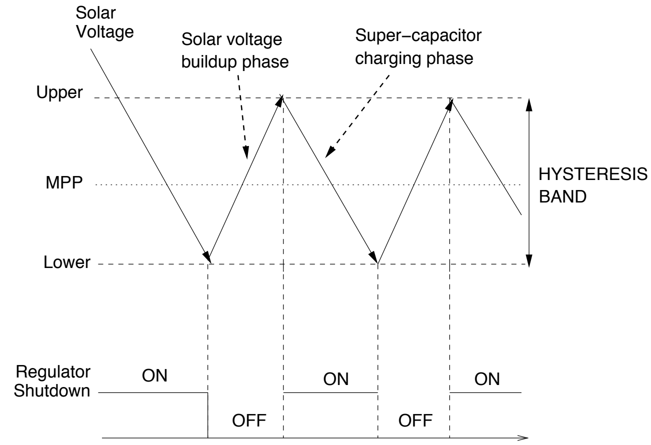


Fig. 7. Charging of Super-capacitor using Maximal Power Point tracking and a switching regulator[28].

charge, the super-capacitors charge the Lithium battery. The block diagram for Prometheus is shown in Figure 5.

Basic components of the Prometheus system architecture (see Figure 5) are, solar panel, primary energy buffer (super-capacitor), secondary energy buffer (Li-polymer battery), charge controller and a power switch interfaced with the Telos sensor node. Compared to single-storage architectures, Prometheus uses an extra stage for storage and a software-based charging control mechanism.

Since all rechargeable battery technologies have a limited number of deep recharge cycles, it is preferable that the battery undergo more shallow recharge cycles rather than deep ones. This is ensured by using a first-stage of super-capacitors, which can undergo theoretically infinite deep recharge cycles. Using super-capacitors as the primary energy source can minimize access to the battery. Hence, battery does not discharge fully and shallow recharge occurs. Further, Prometheus uses a Lithium polymer battery as second-stage storage. The choice of Lithium-based batteries, instead of NiMH batteries, is to avoid the state of memory effect due to shallow recharge cycles.

Prometheus has a software driver to control charging of the energy storage buffers and choice of power source for the node. The *Switch* block shown in Figure 5 is used to switch between the two power sources — the *super-capacitor* and the *Lithium-ion battery*. Figure 6 depicts the logic implemented by the driver to switch between power sources. As shown in the state diagram, so long as the super-capacitor charge is above a high threshold, it is used to power the node. If the super-capacitor charge is above the high threshold and the Li-ion battery charge is below a high threshold, then the battery is charged from the super-capacitor. If the super-capacitor is below a low threshold and recharge opportunity is available, then the super-capacitor is charged. When recharge opportunity for capacitor is not available, then the node is powered from the Li-polymer battery until it falls below the low threshold or until the super-capacitor subsequently gets recharged. As soon as energy becomes available again, the super-capacitor gets charged and on reaching a high threshold, the Li-polymer battery gets charged from the super-capacitor. This logic is implemented using TinyOS[55] on the Prometheus node.

AmbiMax[28] is another double-stage storage energy harvesting system. Similar to Prometheus, AmbiMax has a primary storage (array of super-capacitors of 22F), a secondary storage (Lithium polymer battery of 70mAh). It is built using the Econode[56] platform (consumes 22mA in receive mode and less than 10mA in transmit mode) and harvests solar and wind energy. However, its design is modular enough to accommodate other sources like water flow and vibration.

Unlike Prometheus, the charging control of AmbiMax is accomplished via hardware and not in software. AmbiMax harvests $400mW$ from a solar panel measuring 3.75in $\times$ 2.5in. Each harvesting sub-system, related to each of the energy sources, has its own super-capacitor. AmbiMax performs MPPT (Maximal Power Point Tracking) autonomously, without software or MCU control. Instead of measuring the solar panel voltage, AmbiMax uses light intensity to control a PWM (Pulse Width Modulated) regulator for MPP tracking. The solar energy harvesting sub-system of AmbiMax includes the solar panel, a PWM switching regulator and MPPT circuitry. Figure 7 shows the working of MPPT using the comparator and the PWM switching regulator. When the solar voltage falls below the lower bound of the MPP hysteresis band, the regulator is switched off. It is switched back on only when the solar voltage rises and crosses the upper bound of the MPP hysteresis band. Hence, power is drawn from the solar panel only at maximal power point. Using a PWM switching regulator between the solar panel and the super-capacitor ensures their isolation from each other—neither will the solar panel voltage fall to the super-capacitor voltage nor will there be a reverse current flow from the super-capacitor to the source. This helps in efficient charging of the super-capacitor. A comparator circuit is used to turn on a battery charger when the capacitor voltage is higher than a threshold and the battery is not fully charged.

4) Discussion of Solar Energy Harvesting Sensor Nodes: Table III lists the various solar harvesting nodes that have been described so far. The table shows a comparison along the axes of solar panel power rating, storage type and storage capacity. As can be seen from the table, the amount of energy available/harvestable by each node is different. Heliomote and Fleck1 have solar panels that can harvest over a thousand mWh a day (1140mWh and 2100mWh respectively); so they use a pair of high capacity NiMH batteries. However, Prometheus and Ambimax use smaller capacity Lithium-polymer batteries due to their considerably

TABLE III
SPECIFICATIONS OF SOLAR ENERGY HARVESTING SENSOR NODES.

Node	**Solar Panel Power (mW)**	**Solar Panel Size (inxin)**	**Energy Availability (mWh /day)**	**Storage Type (Y/N)**	**Battery Type**	**Battery Capacity (mAh)**	**Sensor Node Used**	**MPPT Usage**
Heliomote[27]	190	3.75 × 2.5	1140	Battery	Ni-MH	1800	Mica2	No
HydroWatch[26]	276	2.3 × 2.3	139	Battery	Ni-MH	2500	TelosB	Yes
Fleck1[46]	-	4.53 × 3.35	2100	Battery	Ni-MH	2500	NA	No
Everlast[34]	450	2.25 × 3.75	2700	Supercap (100F)	NA	NA	NA	Yes
SolarBiscuit[51]	150	2 × 2	900	Supercap (1F)	NA	NA	NA	No
Sunflower[35]	4 PIN photo diodes 20mW	NA	100	Supercap (0.2F)	NA	NA	NA	No
Prometheus[25]	130	3.23 × 1.45	780	Supercap (two 22F) & Battery	Li-poly	200	Telos	No
AmbiMax[28]	400	3.75x2.5	1200	Supercap (two 22F) & Battery	Li-poly	200	Telos	Yes

better charge-discharge efficiency, compared to NiMH batteries. HydroWatch[26] shows that for a low energy harvesting requirement of $120mWh/day$, NiMH batteries with voltage regulation is enough and much preferred over the complex pulse charging logic of Lithium batteries. Hardware charging is preferred because it guarantees that a node with a fully discharged battery, when placed in the sun, will eventually become active. But lithium batteries need pulse charging[6] and hardware circuits for pulse charging are costly. Hence, [26] uses NiMH batteries which can be trickle charged in hardware.

Prometheus design favours second stage of Lithium batteries because shallow recharge cycles can ensure longer lifetime. With low leakage, high charge-discharge efficiency and no memory effect, Lithium-based batteries are better suited than NiMH batteries to operate with shallow recharge cycles. Prometheus handles the complex charging logic of Lithium batteries through software control. Having software control provides flexibility to re-program/change the harvesting logic and parameters without re-deployment.

In summary, if simple charging control is desired and if energy requirement is moderate or if energy availability is high, then a Hydrowatch-like design is preferred. On the other hand, if charging efficiency is required or energy available is less or flexibility is desired to change harvesting procedure and parameters (implying a software charging control), then a Lithium battery based system may be better suited. Further, in really long deployments, expected to last several tens of years, use of high-capacity super-capacitors seems to be the most viable option. With battery-based storage, the battery will eventually age and die. Replacement and maintenance in such cases, particularly for a large number of nodes, will be prohibitively costly, making the use of super-capacitors attractive.

[6]A Lithium-ion battery needs pulse charging so that the battery reactions can stabilize during the off-time of the pulses.

(a) ZebraNet collar[58]. (b) eFlux node on a turtle[59].

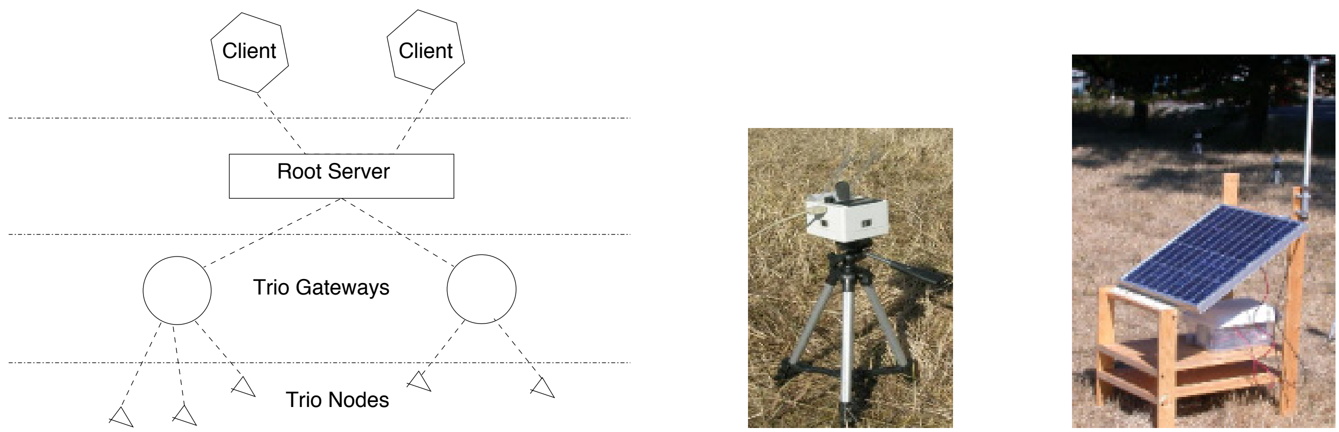
Fig. 8. ZebraNet and TurtleNet energy harvesting sensor nodes.

5) Applications using Solar Energy Harvesting Sensor Nodes: Though energy harvesting sources are many, solar energy is the cheapest, most easily available and convenient source to harvest energy. Hence, there is a host of applications [57], [58], [59], [60] that harvest solar energy for sustained operation. This section lists four representative applications.

• ZebraNet

ZebraNet[58] is a mobile sensor network with sparse network coverage and high-energy GPS sensors to track zebra movement. Continuous locationing using GPS technology tracks the long term animal migration patterns, habitats and group sizes. The ZebraNet collar prototype is shown in Figure 8(a). The ZebraNet collar has 14 solar modules (each having 3 solar cells in series), a simple comparator and a boost converter. Each solar module produces maximum $7mA$ at $5V$. The outputs of the solar modules are connected together in parallel, resulting in the addition of the power generated by each of them. The collar weighs only a few hundred grams and has a peak output of $400mW$.

Zebranet has a Li-ion rechargeable battery for support at night and bad weather. The ZebraNet node is a single-stage storage node, like the Heliomote. However, similar



(a) Trio system hardware architecture.

(b) Trio node mounted on tripod.

(c) Trio gateway.

Fig. 9. The three tier Trio system architecture and its components [57].

to Prometheus, it uses software charging control for pulse-charging its 2Ah Li-ion battery. The Li-ion battery provides the ZebraNet node 72 hours of operation when completely charged[58].

Similar to Everlast and Sunflower, Zebranet is an integrated system. It uses the TI MSP430F149 micro-controller to manage system operations. The micro-controller is also responsible for sensing battery voltage level and pulse-charging it.

• TurtleNet

The goal of the *TurtleNet*[59] is to address the sensing and communication challenges related to the in-situ tracking of turtles. This effort is similar to the ZebraNet project and extends on ZebraNet's design for perpetual wildlife tracking. The TurtleNet eFlux node uses a $250mAh$ Li-ion rechargeable battery that is charged using a solar cell that outputs 90mW at 4.2V. The charging and energy module can handle a wide variety of solar cells. The board is designed to accept a Mica2Dot[45] mote as a drop-in module to the board. The TurtleNet hardware is adapted from the Heliomote hardware design and therefore, is not an integrated system like the ZebraNet node. Figure 8(b) shows the photo of an eFlux node on a turtle. Since the turtles are expected to spend much of their time underwater, the node is made water-proof by packaging it in shrink-wrap tubing and sealing the ends with a water-proof epoxy.

• Trio - Multi-target tracking

Trio[57] is solar energy harvesting node used in a network of static nodes for in-situ sensing. The Trio node builds on the design of Prometheus and implements modifications to overcome some design oversights of Prometheus. The Trio testbed consists of 557 solar-powered Trio motes, seven Trio gateway nodes and a root server[57]. The entire Trio system is a hierarchy of three tiers — Trio nodes, Trio gateways and the Root server (Figure 9(a)). The goal of Trio is to evaluate multi-target tracking algorithms at scale. Figures 9(b) and 9(c) show Trio node and Trio gateway prototypes. While the Trio node itself borrows from the Prometheus design, the Trio gateway node uses a single energy storage design, a large $50W$ solar panel with a large rechargeable gel cell battery and an off-the-shelf battery charging controller.

• SHiMmer

SHiMmer[60] is a wireless platform for sensing and actuation for structural health monitoring. Like Everlast, SHiMmer is also a solar energy harvesting system that uses super-capacitor as storage. SHiMmer uses a technique of localized computation, known as active networking, in which the node actuates a structure, senses vibration and then locally performs computations to detect and localize the damage. Both actuation and sensing are done using piezoelectric elements embedded within the structure, to be monitored via a voltage regulator. SHiMmer uses solar cells to charge a super-capacitor. A boost converter is used to produce the supply voltage for the micro-controller from the super-capacitor. SHiMmer uses the Atmel ATMega128L [47] micro-controller, which has very low power consumption — 1mA in active mode and 5μA in sleep mode.

The actuation and sensing circuits are controlled by a DSP TI TMS320C2811 interfaced with the micro-controller Atmega128. The processing of sensed data to localize faults is also done by the DSP locally. It is possible to harvest enough energy ($700J$) to run the DSP at maximum speed for 15 minutes daily. This is expected to be enough time to perform the fault detection analysis for structural monitoring[60]. The findings are then transmitted using a low-power (13mA-21mA) radio, Chipcon CC1100.

6) Discussion of Solar Energy Harvesting Applications: Table IV tabulates the solar panel characteristics, storage characteristics and the sensor node platform used in the above-mentioned solar energy harvesting applications. These applications either use super-capacitors or batteries as storage, except Trio[57] which uses tiered storage.

ZebraNet node is a single-stage storage system, which uses Lithium batteries (and not NiMH, like Hydrowatch and Heliomote). These Lithium batteries are pulse-charged using the micro-controller software logic, similar to Prometheus. The integrated design provides desired form factor and weight (220 g). TurtleNet node adopts the design of Heliomote, but uses

TABLE IV
SPECIFICATIONS OF SOLAR ENERGY HARVESTING SENSOR NODE APPLICATIONS.

Applications	Solar Panel Power	Storage Type	Storage Capacity	Sensor Node	MPP Tracking	Charging Control
ZebraNet[58]	400 mW	Li-ion	2Ah	Integrated	Yes	Pulse (software)
TurtleNet[59]	90mW	Li-ion	250mAh	Mica2Dot	No	Pulse (hardware)
Trio node[57]	200mW	Super-cap and Li-ion		Telos	No	Pulse (software)
Trio gateway[57]	50W	Gel cell battery	17 Ah	Telos and 802.11 bridge	Off-the-shelf hardware	
HydroWatch[26]	276mW	NiMH	2500mAh	TelosB	Yes	Trickle
SHiMmer[60]	360mW	Super-cap	250F	Integrated	No	Trickle

Lithium batteries instead of NiMH batteries. Thus, though it is not an integrated system like ZebraNet node, the requirement of low self-discharge of the battery still holds and is satisfied using Lithium batteries. Both ZebraNet and TurtleNet are applications for animal tracking, and hindrance in energy availability (turtles moving into water or zebra staying in tree shade) is expected. As a result, Lithium batteries are used to exploit high charge-discharge efficiency and low leakage and maximize harvesting opportunities.

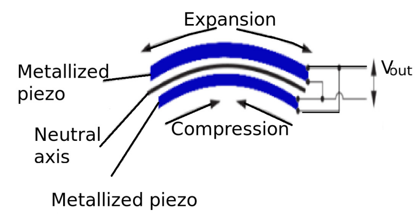
The Trio node adopts the design of Prometheus whereas the Trio gateway node is similar to the Heliomote single-stage storage design, where the solar panel is directly connected across the battery for trickle charging. The Trio node is used in a multi-target tracking application which has high load (20-40% duty-cycling). This falls in line with our conclusion in Section III-A4 that with high load requirements, Lithium based storage is preferred.

SHiMmer is an integrated node like Fleck1[46] but uses super-capacitors. As per conclusion of [46], DC-DC converters are especially useful to efficiently utilize the super-capacitors and along similar lines, SHiMmer uses a boost converter to supply power to the micro-controller from the super-capacitors. Each SHiMmer node itself performs DSP computations to detect and localize the structural damage, and so the power draw is quite less in comparison to that required for transmission of sensed values to a base station. This dramatically cuts down on the power requirement and so SHiMmer nodes do not need high capacity NiMH or Lithium-based batteries; super-capacitors provide sufficient storage.

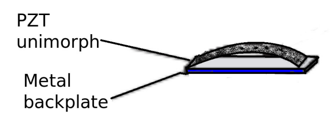
In summary, most of the applications described use Lithium-based batteries, willing to tradeoff charge control complexity for higher charging efficiency and software re-programmability. However, NiMH batteries are also preferred if energy requirement is easily met. The energy requirement of Hyrdrowatch is easily met inspite of lower charge-discharge efficiency of the NiMH batteries. Super-capacitors were not only used to optimize the charging process but also as energy source by nodes in the target tracking and structural monitoring applications. Instantiations of applications requiring low-power using super-capacitor based energy sources, demonstrates their feasibility.

B. Piezo-electric Energy Harvesting Nodes

Piezo-electric energy harvesting nodes use mechanical force to deform a piezo-electric material, which results in an electric potential difference. Two kinds of piezo-electric materials have



(a) Voltage across deformed PVDFs[22].



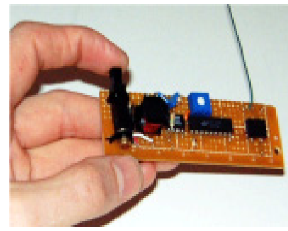
(b) PZT unimorph[22].

Fig. 10. Piezoelectric elements - PVDF and PZT[22].

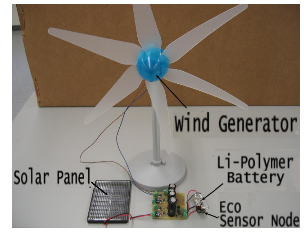
been used to accomplish mechanical-force-to-electric-energy conversion, (i) *piezo-electric films*, e.g., PVDF (PolyVinylidene Fluoride) and (ii) *piezo-electric ceramic*, e.g., PZT (Lead Zirconate Titanate). Piezo-electric films are flexible and exhibit piezoelectric effect due to the intertwined long-chain molecules attracting and repelling each other. On the other hand, piezo-electric ceramics are rigid and their crystal structure is responsible for creation of piezoelectric effect.

1) Piezoelectric-based Harvesting: PVDF is a piezo-electric film which produces an electric potential across its terminals when deformed (stretched or bent). When the PVDF stave is bent, the PVDF sheets on the outside surface are pulled into expansion, while those on the inside surface are pushed into contraction (as depicted in Figure 10(a)), producing voltage across the terminals. Similarly, charge develops across the faces of the PZT strips when the PZT dimorph is compressed or released to produce a voltage across the two ends. A PZT unimorph is shown in figure in 10(b). Two such PZT unimorphs on either side of the metal backplate form a PZT dimorph. Ordinarily, the PZT unimorph has a curved structure. When pressure is applied, it is pushed and stretched, thus generating an electric potential by piezo-electric effect. PZT, being a ceramic, is not as flexible as PVDF. It can not handle outward stress and hence a rigid metal backplate is used to prevent damage of the PZT unimorph. In order to enable energy scavenging, activities like walking, foot strike and finger motion, can be used to deform the PVDF or PZT.

Fig. 11. Functional prototype of piezoelectric-powered RFID shoes with mounted electronics[22].



(a) Self-powered push button transmitter[21].



(b) AmbiMax wind energy harvestor[28].

Fig. 12. Piezo and Wind energy based harvesting nodes.

2) Shoe-powered RF Tag System: The shoe-powered RF tag system is an example of piezo-electric based energy harvesting system. It is a self-powered, active RFID tag wireless transmitter that sends a 12-bit identification code over short distances, while the bearer walks. A PZT dimorph is used under the heel of a shoe to harvest heel strike energy of the bearer[23] and a PVDF stave can be inserted inside the shoe sole[22], [23], [24] to harvest energy from walking motion. Experiments showed that PVDF produces $1mJ$ per step whereas PZT produces $2mJ$ per step. The energy scavenged using either PVDF (peak power 20mW) or PZT (peak power 80mW) is used to encode and transmit a periodic RFID signal[23]. These beacons can be exploited to track mobile users and to disseminate location-aware information. Figure 11 shows the functional prototype pair of self-powered sneakers developed by Paradiso et.al[22].

3) Wireless, Self-Powered Push-Button Controller: The self-powered push-button controller described in [21] is able to wirelessly transmit a digital code to a distance of 50 feet on a single button push. The system is pictorially depicted in Figure 12(a). It does not need batteries since it generates energy from the energy expended in the button push.

A piezo-electric conversion mechanism is employed to harness energy from the push motion. The push energy impacts the PZT element and it self-oscillates at its resonant frequency. A step-transformer couples the high voltage/low current from the piezoelectrics to a low voltage/high current of standard electronic circuitry. After rectification, the electrical energy is stored in a capacitor. It is regulated down to the required 3V of the RF transmitter circuitry. The RF circuitry can transmit the 12-bit digital code upto 50 feet.

The systems described above are instantiations of using piezoelectric materials for harvesting mechanical energy. Harvesting significant amounts of human power needs sustained effort for long durations due to the very small amount of energy harvestable. Up till now, these energy sources have not been used in wireless sensor network deployment. An open direction is engineering and research to develop piezo-based harvesting sensor nodes which intelligently combine human activities and energy harvesting.

C. Other Harvesting Sources

1) Wind Energy Harvesting Nodes: An implementation that harvests wind energy is *AmbiMax*[28]. As mentioned in Section III-A3, AmbiMax is a system that is built to accommodate various energy sources. AmbiMax implementation[28] on the Eco node [56] harvests wind energy using a wind turbine, shown in Figure 12(b). The rotor speed output is used to perform MPPT[7]. The rotor's frequency is fed to a FV (frequency-to-voltage) converter, which outputs the appropriate voltage signal.

The work in [28] indicates that it is indeed possible to harvest wind energy for use in wireless sensor networks. However, size of the wind turbines can be an issue, turbines used in AmbiMax have a body length $200mm$ and blade sweep radius of $155mm$. As compared to small form-factor nodes, these dimensions are much larger and an added constraint for deployment. Another effort in harvesting wind energy is presented in [30], which utilizes the motion of an anemometer shaft to turn an alternator and uses a pulsed buck-boost converter to convert the motion to battery potential.

2) Radio Frequency Energy Harvesting: When a time-varying electromagnetic radio frequency (RF) field passes through an antenna coil, an AC voltage is generated across the coil. A magnetic coupling due to mutual inductance generates voltage. In RF energy harvesting, a passive RF tag uses RF energy transmitted to it, in order to power itself — a form of energy harvesting. This is not applicable to active RF tags, which have their own battery supply and do not depend on external RF energy for their power requirements.

In RFID systems, an RFID reader queries an RFID tag, which in turn, responds with its own identification. This is used to identify, locate and track people, assets and animals. The RF signal is sent by the RFID reader and the RFID tag is energized by the voltage obtained from the mutual inductance of their loop antennas[38] as depicted in Figure 13.

The response of the tag involves amplitude modulating the received carrier signal according to its own identification data that is stored in non-volatile memory. This is called *back-scatter modulation*. The RFID reader keeps sending out RF signals and monitoring the reflections for change in amplitude. Any amplitude change denotes presence of an RFID tag. Thus, unlike normal sensing applications where the sensor itself harvests energy, here the sensor (RFID reader) senses the presence of the energy harvestor (RFID tag)! Applications on similar lines, with nodes doing more than just sending back their identifications would be an interesting direction to pursue. An example scenario would be a mobile data sink moving in an area of interest and source nodes harvesting RF energy from the sink and feeding data of interest back to it.

One such interesting application of RF energy harvesting is

[7]Maximal Power Point Tracking

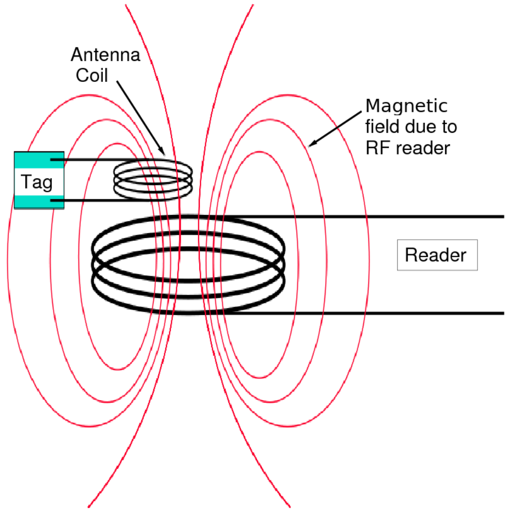


Fig. 13. Magnetic coupling between tag and reader loop antennas [37].

Computational RFID (CRFID) [39], [40], [41], [42]. Computational RFIDs are RFIDs that store harvested energy and use it for general-purpose computation. Example applications of CRFID usage is for structural monitoring [42] and implantable medical devices [61]. Wireless Identification and Sensing Platform (WISP) [39], [40] is a CRFID which uses an ultra low power TI MSP430F1232 [54] microcontroller (upto 8MHz) for general-purpose computation. CRFIDs face the major challenge of operation under continuous interruption in energy availability and small quantities of harvestable energy. Typically, CRFIDs may have an average active life duration even as small as a second or lesser [41]. Such low amounts of energy are insufficient to charge a rechargeable battery, hence a capacitor is used. Further, solutions addressing the issues of computation distribution over multiple charging cycles and ordering of tasks is required for increasing productivity of available RF energy [41]. Additionally, there are efforts to supplement CRFIDs with solar power (by equipping it with a 11.4 cm^2 solar panel [42]).

This section described implementations of energy harvesting nodes using energy sources like solar, wind, human power and RF energy. Solar energy is the cheapest, most easily available, and most easily harvestable source of energy. Though wind energy is also an ambient source of energy (and hence easily available), but wind energy harvesting equipment is bulky compared to sensor node sizes and its conversion efficiency is much lower as compared to solar energy harvesting. In case of harvesting human power, sustained effort by the human is needed to harvest sizeable amounts of power. Hence, solar energy as a harvestable source is most popular for energy harvesting in wireless sensor network deployments.

IV. Implications on Sensor Network Systems and Solutions

Sensor network applications are optimized for several different design parameters—lifetime, sensing reliability, sensing and transmission coverage, and cost, to name a few. Traditionally, sensor networks and their solutions have been designed with finite energy as the primary constraint. A sensor network optimized for increased lifetime may operate nodes at low duty-cycles and compromise sensing reliability in the process. A network optimized for reliability and coverage will have to operate with larger batteries, or will involve periodic human effort to change batteries, or will have a dense and redundant deployment, all of which will increase cost. As a result, battery-powered nodes most often meet only a subset of these potentially conflicting application design goals. With the advent of energy harvesting and recharge opportunities, the basic optimization constraint of finite energy is less stringent and in many cases, does not hold.

Recharge opportunities impact both individual node operations as well as system design considerations. For example, if a node can predict its next recharge cycle, it can optimize (increase) its capability by tuning different node parameters like sampling rate, transmit power, duty-cycling etc. To exploit these possible added benefits, the node has to predict the next recharge cycle—its duration, starting time and expected amount of harvestable energy. Simultaneously, the node needs to choose and tune parameters in a manner that does not exhaust available energy before the next recharge cycle. Thus, by exploiting recharge opportunities and adapting node functionality, energy harvesting sensor nodes can address conflicting design goals by simultaneously optimizing for lifetime and performance. Further, solutions built using energy harvesting nodes have network-level implications. For example, in the presence of recharge opportunities, routing metrics can not only take into account traditional metrics like hop count and delivery probability, but also be cognizant of current and future energy levels at intermediate nodes. For example, a routing protocol may prefer a shorter path having nodes expecting to replenish their energy in the near future, over a longer path which may have nodes with higher current energy levels. Thus, the presence of recharge opportunity can be exploited for higher performance, shortest path in this case.

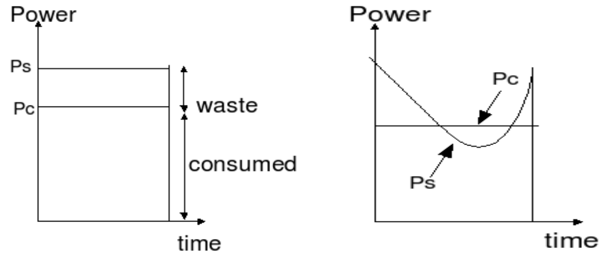
Harvesting opportunities allow tuning of node-level system parameters and directly impact the design of sensor network applications and solutions. The rest of the section elaborates and discusses these implications.

A. Energy Neutral Operation

Energy-neutral operation is a vital challenge towards balancing energy usage and maximizing performance based on current and expected energy levels.

Node-level energy neutrality implies maximizing a node's performance and simultaneously ensuring that the node never fails owing to energy depletion. A node takes current and expected energy levels into account, dynamically tunes performance and simultaneously ensures that the node neither operates below minimum performance levels nor switches OFF before the next recharge cycle. Node-level energy neutral operation is the perpetual functioning of a sensor node, i.e., energy usage of a node is always less than the harvested energy. Based on the type of energy harvesting architecture used, node-level energy neutral operation has different implications.

Let $P_s(t)$ be the power output from a energy source and $P_c(t)$ be the power consumed by the sensor node at time t. The condition for energy neutral operation for the two energy harvesting options is as follows[20],



(a) Harvest-Use (b) Harvest-Store-Use

Fig. 14. Example power consumption trends of harvesting architectures. P_s and P_c are the source and consumption power levels, respectively.

Harvest-Use System: In this case, the energy harvested is directly (and continuously) used by the sensor node. A necessary condition for energy neutral operation is, $P_s(t) \geq P_c(t)\ \forall t$. If the harvested energy is more than that consumed by the node, it simply gets wasted. On the other hand if harvested energy is less than required, the node does not operate. As shown in Figure 14(a), $P_s(t) - P_c(t)$ is the energy wasted with energy neutral operation in a *Harvest-Use* system.

Harvest-Store-Use System: A critical component of this system is the storage unit. An ideal storage unit is that which has infinite capacity, can transfer 100% of the energy input from the charging source to the storage unit and restores the same energy level until used. A practical storage unit has finite capacity, has less than 100% charging efficiency and suffers from leakage even at zero load.

Figure 14(b) shows an example scenario of the power output of the energy source and the power consumed by the sensor node with time. A *Harvest-Store-Use* harvesting system, can satisfy energy neutral operation condition even if $P_s(t) < P_c(t)$ for some time instants. With B_0 as the initial residual storage energy and with ideal storage, the following inequality needs to be satisfied at all times for energy neutral operation over a time duration T.

$$B_0 + \int_0^T [P_s(t) - P_c(t)]\ dt \geq 0 \tag{1}$$

In case of a non-ideal storage unit, the inequality includes the leakage power (P_{leak}) and finite storage capacity B, and can be stated as follows,

$$B \geqslant B_0 + \int_0^T [\eta P_s(t) - P_c(t) - P_{leak}(t)]\ dt \geqslant 0 \tag{2}$$

η is the conversion efficiency of the harvesting mechanism.

Application-level energy neutrality implies meeting application requirements at all times as long as harvestable energy is available, e.g., providing continuous sensing coverage to a region. While node-level energy neutrality is concerned with operating each node within permissible limits, application-level neutrality implies co-ordination and cooperation amongst nodes to tune system parameters and meet application requirements. Though node-level energy neutrality ensures application-level energy neutrality, the reverse is not necessarily true. Consider two closely placed nodes. They can decide to adjust their parameters such that one node is ON and the other OFF. The OFF-node becomes operational only when the ON-node's energy levels deplete and fail to meet application requirements. The sequential operation of the nodes meets application requirements in-between recharge cycles (thus ensuring application-level energy neutrality), but does not ensure node-level energy neutrality on either node.

Though node-level energy neutrality implies all nodes are perpetually ON and application-level energy neutrality implies at least a subset of them is ON, nodes can operate in other modes as well. A node can independently operate at levels that exhausts its battery before the next recharge cycle. On replenishing its energy level after a recharge cycle, the node is functional again. Irrespective of the mode of operation, the node can exploit recharge opportunities for periodic or continuous operation.

B. Performance Adaptation

To exploit the possible performance benefits, energy-harvesting sensor nodes need to perform tasks which they would traditionally not perform when operating with finite battery capacity. A node can potentially choose from a set of system parameters for increased capability and performance. These parameters—duty-cycling, sampling rate, transmission power, data processing etc. need to be carefully chosen in accordance with the next recharge cycle. A primary requirement for any node-level optimization is a *prediction* module which models the availability of harvestable energy. *Effective energy*—a function of the expected energy from recharge in a subsequent duration, the energy consumed by non-optional tasks and the current battery level—can be used to simultaneously tune different system parameters and also meet the energy neutrality constraints.

• **Energy Prediction Methods:** An energy harvesting node can tune various system parameters for performance optimization as well as maintain energy neutrality, provided it is able to predict the available or harvestable energy. For example, with solar energy, the node should be able to predict the recharge cycle and more importantly, the expected harvestable energy, over a duration of time.

An energy harvesting framework (EEHF) to predict a node's *effective energy* is presented in [62]. The approach considers a day as a single epoch and uses an autoregressive filter on energy consumption and energy availability over finite number of previous epochs, to predict the energy available in the next epoch. Effective energy is formulated as a weighted function of the predicted expected energy, the energy consumption and the battery level. Another framework, Enhanced-EEHF[63], extends EEHF and uses the concept of rounds within each cycle/epoch to obtain a more accurate effective energy estimate. It obtains a first estimate of the expected energy for a round of a particular cycle, using the estimated and generated energy of the same round of the previous cycle. The estimate is further refined using the estimated and generated energy of the previous round of the same cycle. This approach improves accuracy by accounting for both the history across cycles and the trend of energy availability and consumption in the current cycle.

An alternative approach to energy availability prediction uses an Exponentially Weighted Moving-Average (EWMA) filter [20]. Here, a day is divided into forty-eight half hour slots, and energy available during each slot is estimated using a weighted average of the energy availability in the same slot over previous days and energy estimate of the previous slot. Using appropriate weighting factors, the prediction can adapt to seasonal and diurnal variation in energy availability. The average energy availability of a slot, $\overline{x}(i)$, is estimated using the following equation,

$$\overline{x}(i) \quad = \quad \alpha\overline{x}(i-1) + (1-\alpha)x(i) \tag{3}$$

$x(i)$, is the actual generated energy in slot i, $\overline{x}(i-1)$, the average energy availability in slot $i-1$ and α the weighting factor. For a slot, its average energy availability over the previous days, estimated using the above equation, is used as the current prediction of the energy available in the slot. For each slot, the weight for older slots decreases exponentially. A weighting factor of 0.5 was empirically found to be an optimal value for minimum prediction error [20]. Since, the energy availability for a slot is updated at the end of every slot, its adapts to energy availability variations across days. Further, the model could be optimized to tune the value of α as well based on seasonal patterns.

• **Node-level Adaptations:** Each node can independently, or in coordination with other nodes, use the effective energy estimates to choose and tune parameter settings. The parameters that need to be changed in order to positively influence performance metrics are largely a function of the application and solution requirements. Following is a list of potential system parameters that a node can tune based on its effective energy estimate.

1. Duty-Cycling: Duty-cycling is the fraction of time a node is ON in a cycle of ON and OFF durations. The duty-cycling parameter of a node affects its performance and energy usage. A node with a higher duty-cycle uses energy at a quicker rate, but can provide benefits of higher sampling reliability and lower communication delay. Traditionally, variations (if any) in the duty-cycle of a node are done to meet lifetime requirement based on the finite energy constraint. With energy-harvesting opportunities, the energy constraint is relaxed and the duty-cycle parameter can be tuned more often (per epoch) and possibly maintained at higher levels. Based on the predicted effective energy, nodes can adjust their duty-cycle parameters—higher duty-cycles for nodes with higher effective energy and lower duty-cycle for those with lower effective energy.

A mathematical model to predict the ideal battery size and the rate of availability of harvestable energy is proposed in [20], [33]. The model is used to dynamically vary the node duty-cycle to maximize performance and also ensure node-level energy neutrality. The approach uses a non-decreasing function to model the relationship between node utility (performance) and duty-cycle. Thresholds of minimum and maximum duty-cycling, correspond to minimum and maximum utility, respectively. Initially, optimal duty-cycles are computed for each slot using the predicted values for energy availability. However, dynamic adjustment of this duty-cycle is necessary because the actual available energy in a slot may not be the same as the predicted value. The solution uses the difference between predicted and available energy levels to increase or decrease the duty-cycle parameter dynamically. If there is excess energy available, then the duty-cycle is proportionally increased for the next slots whereas if there is deficit in energy availability, then the duty-cycle is reduced in subsequent slots to compensate for it.

Reduction in duty-cycle variance in the presence of highly variable energy availability is done in [64]. Unlike [33], apriori knowledge of the energy profile is not assumed and duty-cycle is determined based only on current battery level. Similar to [33], the goal is to achieve Energy Neutral Operation (ENO) and Maximum performance, the dual condition referred to as the ENO-Max condition. An objective function is defined which minimizes the average square deviation of the battery from its initial level. This implies that the battery energy is not in deficit as well as all the energy being harvested is being used optimally. A Linear Quadratic (LQ) tracking problem is formulated using the above objective function as the cost function so that the duty-cycle computed maintains the specific battery level. Further, stability of duty-cycle is achieved by using an exponentially weighted moving average of previous outputs of the LQ tracker.

The approach in [33] uses a utilization metric derived from the application to compute the minimum and maximum desired duty-cycles and duty-cycle is varied dynamically such that it is held within these thresholds. On the other hand, [64] does not need such inputs from the application level and instead uses adaptive control theory to reduce the variability in duty-cycle, and at the same time, holding it as high as possible while ensuring energy neutrality.

2. Transmit Power: One of the highest power consuming components of a sensor node is the wireless radio. Setting radio transmit power to a moderate or low level is one of the mechanisms to reduce the energy used for communication. Based on application requirements and availability of external hardware like an antenna, traditional battery powered nodes have a fixed setting for transmit power or one which does not change too often[65]. A survey of power-control techniques in wireless sensor networks, is presented in [66]. The main objective of these techniques is efficient energy usage. The energy conservation mechanisms are categorized as Active and Passive. Passive energy conservation entails switching off the radio interface (parallel to the duty-cycling concept discussed above) whereas Active energy conservation consists of adjusting the radio transmit power using adaptive protocols to conserve energy. While tuning of transmit power in battery powered devices is aimed at optimizing energy usage, transmit power adaptation in energy harvesting nodes can also be used to increase communication range of the node and increase efficiency of data dissemination protocols.

Similar to duty-cycle variations, a node can adjust transmit power based on the predicted effective energy [67]. In [67], each node uses localized information about its neighbourhood to make routing decisions based on metrics like low latency or low energy consumption. The topological extent of this localized information is defined as the node's *knowledge range*. The knowledge range of each node is computed based on its current energy, expected energy and energy consumption in the next period. Smaller the desired knowledge range, lower the transmit power and vice versa. Each node chooses the next hop node within its knowledge range. Since higher transmission power implies larger communication ranges, a node with higher transmit power will have larger set of neighbors and a larger set of available communication links for data-forwarding[67]. Transmit power values are mapped to corresponding expected energy usage, and energy neutral operation is ensured (assuming no node-level sleep periods) based on the predicted effective energy.

3. Sensing Reliability: Sensing reliability is the quality of information provided by the sensor. Similar to a node's duty-cycle and transmit power, sensing reliability has a tradeoff with energy usage. One of the deciding parameters of sensing reliability is the node's sensing frequency—greater the frequency, greater is the sensing reliability. With battery-operated nodes, sensing frequency is seldom changed. However, with energy harvesting nodes, sensing reliability can be varied proportionally with the predicted effective energy—greater the effective energy, greater is the reliability and vice versa. The actual mapping of sensing frequency and effective energy depends on the energy cost associated with sensing. A linear programming formulation is presented in [68] to maximize the sensing rate under the constraint that the energy in storage be non-negative within the prediction interval. The approach splits a day into a finite number of prediction intervals, and the sensing rate of each such interval is maximized depending on the initial storage energy, the predicted energy and sensing rates of the previous prediction intervals of the same day. An online controller computes optimal sensing rates for all prediction intervals of a day at a time. It compensates for the unstable power supply and holds the sensing rate almost constant.

Sensing reliability of applications like detection using vision sensing, also depends on the amount of processing at the sensor node. A vision sensor node can perform limited processing on captured images to flag the detection of an object based on simple background subtraction algorithms, or processes the image further to classify the detected objects or approximate their location [16]. Each of the processing options has different energy costs and different sensing reliabilities. In such cases, the amount of processing at a sensor node can be varied proportionally with the predicted effective energy and higher sensing reliability can be obtained whenever possible.

4. Transmission Scheduling: As discussed earlier, wireless transmission uses relatively higher energy than other tasks. One technique to reduce the number of transmissions is to aggregate data from various nodes at intermediate nodes and transmit fewer messages. Similarly, data at a single node can be aggregated in a temporal manner to send collective information and reduce the number of transmissions. These techniques can be optimized further to account for energy harvesting nodes. Energy harvesting nodes can be responsible for data aggregation and transmission. Further, these nodes can schedule data dissemination based on predicted effective energy. With solar-powered nodes, effective energy is closely related to time-of-day. A possible approach is to have harvesting nodes schedule immediate transmission of all aggregated data during the day. Whereas, during night, the harvesting nodes primarily only sense, collect data from neighbors for aggregation, store the data and perform other critical tasks, if any. Transmission of stored aggregate data can be scheduled for later, when recharge opportunities are available. As a result, transmission scheduling—toggling between low-power and high-power states—can be vital for continuous sensing and data collection. An important requirement is to accurately estimate the patterns of energy availability, to switch between the high and low power states.

• **Network-level Design:** So far in this section, we have seen how functionality of individual nodes can be tuned to exploit the presence of a harvestable energy source and improve performance parameters. Presence of such energy harvesting nodes as part of the network, has an impact on network-wide solutions and protocols. For example, varying the duty-cycle of a node will result in varying latencies during data dissemination. Similarly, varying the transmit power will change the available routes through the node and its neighbourhood set. Following are examples of changes to traditional solutions which aim to exploit the presence of energy harvesting nodes,

1. Routing: Routing protocols like Directed Diffusion [10], depend on gradients from the data source to sink for route setup. Usually, the *best* route is the one that delivers the first response from the source to a data request query from the sink. Other route selection metrics include delivery probability and number of hops. Traditional sensor network routing protocols also incorporate energy-based metrics to account for residual energy levels at nodes for routing decisions [69], [70], [71]. A taxonomy of energy efficient multicast routing protocols [72] classifies them as, "active energy saving", "passive energy saving", "topology control" and "maximizing network lifetime". Active energy saving protocols try to find a routing path with minimum cumulative energy usage. On the other hand, maximizing network lifetime protocols focus on equitable energy usage across all nodes. A single node failure implies network failure in this scenario. Passive energy saving protocols involve turning off as many radios as possible while maintaining connectivity, whereas topology control protocols involve tuning transmit power levels to maintain desired connectivity and simultaneously minimizing energy usage.

Energy harvesting adds another dimension to route selection, that of effective-energy-aware route selection. Consider a network consisting of battery-powered and energy harvesting sensor nodes. An end-to-end residual energy routing metric can select energy harvesting nodes as intermediaries for routes. Battery-powered nodes will then be used only as last hop nodes or as intermediaries only when no energy harvesting neighbor is in the vicinity[73]. Further, since the duty-cycle of each node on a route affects the end-to-end latency, it is beneficial to have more energy harvesting nodes on the chosen route[74]. These energy harvesting nodes tune their duty-cycle to higher values when the effective energy is higher. Thus, the routing metric of *effective energy* at each node, along with other metrics of link quality, duty-cycle etc., has the potential to decrease routing responsibility and increase the lifetime of battery-powered nodes. Maximizing the number of energy harvestable nodes on routing paths has the potential to increase the overall lifetime of the network[8].

In order to choose routing paths according to energy distribution, [75] uses the EEHF model to predict the effective energy at each node and proposes a routing metric based on this energy value. A directed graph of the network is created with the inverse of a node's effective energy as the communication cost for all edges into that node. A routing path that minimizes the end-to-end cost for a given source-destination pair, exploits availability of effective energy.

In the earlier discussion on duty-cycling, we cited [74] which dynamically computes duty-cycle based on energy harvested, energy consumed and initial battery level. Dynamic changes in duty-cycle will affect communication latency from source to destination The total latency along the path is a summation of delays at each node along the path. As a result, higher the duty-cycle of the node, lower the path latency and vice versa. The approach in [76] builds on this duty-cycle computation and proposes three low-latency routing algorithms for duty-cycling nodes. Each node compares the first-hop latencies or second-hop latencies or full-path expected latencies, respectively, to choose the next-hop neighbour for routing. Comparing the first-hop latency only, is short-sighted since the second hop maybe contributing a higher value to the path's total latency. Accounting for second-hop latencies before choosing the next-hop node for routing, is a more latency-cognizant decision. Using full-path expected latencies for routing will result in the optimal path at the cost of increased number of *update* messages. If a routing algorithm has to be "far-sighted", every node has to exchange information about its state periodically, or on demand, thus adding to routing overhead.

Some alternative routing algorithms for duty-cycling nodes, based on harvesting-aware duty-cycle computation [74], are presented in [67] and [77]. In [67], different routing protocols are used for data of different priorities—the shortest or the least latency path for delay-sensitive data, the most energy-efficient path for non-delay-sensitive but critical data and multiple paths for sensitive and critical data. The approach in [77] builds on work done in [67] and [76], and proposes a low-latency geographic routing algorithm for asynchronous energy harvesting nodes that perform duty-cycling. Low-latency is achieved by locally computing the expected latency to sink, using geographic location of neighbours and latency values to their potential neighbours.

2. Clustering: Another useful mechanism to route packets in sensor networks is through formation of clusters. Nodes route packets to cluster heads, which in turn, transmit packets on a cluster-head overlay to reach the destination [9], [78]. Cluster formation and cluster head selection are important issues to address in this category of solutions. Harvesting-capable nodes, with regular recharge opportunities, are suitable candidates to be chosen as cluster heads[79]. Battery-powered nodes act as cluster members as often as possible, route packets to harvesting-capable cluster heads and minimize power consumption. sLEACH[79], an extension to LEACH [9], is a harvesting-aware clustering technique for routing data. Using a notion of rounds, sLEACH probabilistically chooses cluster heads for each round to spread the routing load. The probability of harvest-capable nodes is set to higher values than battery-powered nodes. To do this, a constant weighting factor is assigned to solar-powered nodes and its reciprocal is assigned to battery-powered nodes. As a result, if harvesting nodes exist in a cluster, one of them will be chosen as a cluster head with high probability. A cluster-head that has subsequently switched to battery operation, can toggle its weighting factor and handover its responsibility to another solar-powered node. As compared to LEACH, which assigns uniform probabilities to all nodes for cluster head selection, sLEACH is demonstrated to increase the overall lifetime by 10%-45% in a network ranging from 5 to 25 energy-harvesting nodes[79].

Experimental evaluation of sLEACH is based on simulation and simple correlations of harvesting availability and recharge. Interesting extensions to sLEACH would be to evaluate it based on a prototype deployment and from energy availability traces to understand its improvement in realistic environments. Further, sLEACH assigns a fixed weighting factor to all harvesting-capable nodes (assuming homogeneous harvesting availability and capability). Correlating the weighting factor to the effective energy, the harvesting periodicity and the residual energy at each node would make the approach more generic. One such extension is presented in [63], wherein each node assigns itself a cost depending on its predicted and residual energy and its minimum required consumption energy. Higher the surplus energy, lower the cost. Each such potential cluster-head waits for a time proportional to its cost before sending out an advertisement. Any node that receives such an advertisement will be a member of that cluster. Ties in cluster-head selection are resolved by choosing the one which requires less transmission energy. Isolated nodes become members or sub-members of nearby clusters or form single-member clusters of their own. This approach has been shown[63] to guarantee better clustering than probabilistic clustering.

Clustering is a useful technique to mask network connectivity and topology changes. Applications, like data collection and data routing, can co-ordinate with cluster-heads for their operations. Cluster-heads in-turn can co-ordinate with the dynamic set of nodes. Clustering techniques that provide this benefit in mobile environments are presented in [80], [81]. These techniques can be extended to adapt to not only mobility but also to topology changes caused by adaptive control of other harvesting-based node-level parameters like transmit power, duty-cycling etc.

3. Data Collection: Several sensor network applications require periodic collection of data, with higher rates translating to better quality. Battery-powered nodes, with finite energy capacity, use low data rates in favour of extended lifetime. A method for energy-efficient data collection is using data-aggregation techniques. While data-aggregation techniques have been proposed [82] to efficiently gather data on the axes of energy, accuracy, reliability, latency etc., harvesting makes the choice of in-network aggregation decisions more dynamic. Further, short-term and long-term aggregation locations and

[8]Overall lifetime of a network is defined as the time before the first node in the network reaches end-of-life.

policies can be formulated based on harvesting potential at each node and the expected workload.

An approach for high throughput data extraction from all nodes in the network while meeting per-node energy neutrality constraints, is presented in [83]. An optimal lexicographical rate is estimated with the aim of maximizing the minimum data rate across all nodes. With a lexicographical rate assignment, it is not possible to further increase the rate of one node without decreasing the rate of another. The rate assignment problem is formulated as a linear optimization problem, and both centralized and distributed solutions are proposed. The centralized approach accounts for effective energy at nodes (i.e., predicted and residual energy) and computes the data rates and routes from each source to a single sink. The distributed solution assumes prior knowledge of routes to the sink and solves the data rate assignment problem.

Attempts to maximize data rate have also been made in [84], [85]. A new metric is introduced, MESW (Maximum Energetically Sustainable Workload), which refers to the maximum workload that can be sustained by the network under given energy constraints. Similar to [64], that maximized node duty cycle while ensuring energy neutral operation, the MESW metric aims to maximize the data rate at each node with energy neutrality. A network graph annotated with channel capacities is used to find the maximum flow between any two nodes by solving the *Maxflow* problem. However, this assumes that each node has infinite flow capacity. The MESW approach [84], [85] adds the constraint of each node having limited flow capacity through it and thus formulates a *node-constrained* network flow problem. The maximum data rate is then computed by solving the maxflow problem on the node-constrained network flow graph.

4. Miscellaneous:

Consider the problem of deploying a sensor network to provide sensing coverage to a given region of interest. Traditional techniques rely on redundant and dense placement of nodes [18], [19], with nodes coordinating and operating in subsets to address coverage and lifetime requirements. With energy harvesting, if the harvestable energy of a node is such that it can operate for long periods, lesser redundancy in node placement maybe sufficient to meet coverage requirements for longer durations. The problem of interest would be to come up with a placement technique that maximizes the number of locations for placement of harvesting-aware nodes. As a result, minimizing the number of battery-powered nodes has the potential to decrease the number of redundant near-located nodes, resulting in cost reduction and also longer coverage guarantees.

Another potential implication of harvesting is on MAC layer protocols. Several sensor and wireless network MAC protocols [86] exist—CSMA-based and TDMA-based. CSMA and low-power listening based MAC protocol like BMAC [7] and XMAC [8] use sender-based preambles to intimate receivers of incoming data. Receiver initiated versions, like RI-MAC [87], do not send preambles. Instead, a sender remains awake till it hears a beacon from the intended receiver. The above protocols work with duty-cycled nodes and the length of the preamble or the time for which sender waits for a receiver depends on the sleep period of the receiver. The duty-cycle parameters are fixed and seldom change when operated with battery-powered nodes. In presence of harvesting, based on the effective energy at a node, the preamble length or wait duration can be increased or decreased to allow energy-scarce nodes to sleep for longer durations. The problem of relating expected energy levels of all nodes in the network, their routing paths and traffic patterns, with duty-cycle and MAC parameters of each, is of potential interest. Further, with TDMA-based MAC protocols [6], [88], [89], nodes are either assigned a fixed number of slots or allotted slots on request. Harvesting nodes can be assigned, or can request for, slots as a function of their expected energy. Nodes with higher levels of expected energy can use multiple slots in a round for communication. As a result, a potential direction to explore, is the automatic assignment of slots for nodes based on their expected energy and traffic patterns.

In this section, we described various node-level and network-level implications of energy harvesting on sensor network design. Potential node and network-level parameters to tune and affect network design and performance were presented. As discussed above, system design and node-level adaptations are inter-dependent. Tuning of node-level parameters affects network solutions and communication protocols, e.g., change in transmit power changes neighborhood and affects routing metrics, variations in duty-cycle affect MAC parameters, change in node sensing rates affect network data collection. This reasserts the point that design considerations of sensor network applications and node-level power management mechanisms are tightly coupled. The description of node-level and network-level implications presented examples and potential directions of solutions to exploit harvesting opportunities in order to simultaneously improve performance parameters and network lifetime.

V. Conclusions

The capability of a wireless sensor node to harvest energy has the potential to simultaneously address the conflicting design goals of lifetime and performance. In this paper, we discussed various aspects of energy harvesting systems. We presented basic concepts of harvesting systems—architectures, types of harvestable energy sources, and storage technologies. We described details of existing energy harvesting sensor nodes and applications, most notably the ones dependent on solar energy. Further, we presented insights into implications of recharge opportunities on node-level operations and design of sensor network applications and solutions. We believe these insights will motivate further research towards usage of energy harvesting sensor nodes and their applications.

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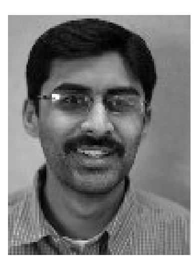

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