# Reincarnation in the Ambiance: Devices and Networks with Energy Harvesting

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***Abstract*—Miniaturization of devices with higher computational capacity coupled with advancement in communication technologies is driving the growth of deployment of sensors and actuators in our surroundings. To keep up the pace with this growth, these tiny, battery-powered devices need small-sized and high-energy density batteries for longer operation time, which calls for improvement in battery technologies. An alternative is to harvest energy from the environment. An important aspect of energy harvesting is that the devices go through birth and death cycle with respect to their power unlike battery powered ones. Another important aspect is that context information is also generated while devices harvest energy from their ambiance. In this article we provide a comprehensive study of various types of energy harvesting techniques. We then provide some models used in energy harvesting systems and the design of such systems. We also throw light on the power management and networking aspects of the energy harvesting devices. At the end we discuss the major issues and avenues for further research.**

***Index Terms*—Ambient Energy Harvesting, Applications of Energy Harvested Networks, Wireless Sensor Networks, Energy Storage, Harvested Network Protocols**

## I. INTRODUCTION

Wireless devices or nodes such as sensors and actuator networks have become now a part of many systems and areas such as health care, factories, home automation, etc. These battery operated devices or nodes die in the field if their batteries get depleted. By equipping devices to extract energy from their surroundings, energy harvesting devices have the luxury of being "born again" when they have accumulated enough energy from the ambiance to revive themselves[1]. Energy harvesting thus promises to provide a means for the widespread use of wireless sensor networks and other embedded devices that require to be autonomous and deployable in hostile but ambient energy rich environments. The lifetimes of these devices can be improved to a few decades, while also reducing the cost of maintenance. However, running a single node, or networking with harvested energy is not without challenges. Current research has identified and proposed solutions for various issues such as power management routing, MAC and scheduling. Aspects of an energy harvesting device and the network to which it belongs have been modeled well. These aspects include the traffic load, the energy harvesting mechanism, the energy harvested and usage profile, applications and requirements of the network and so on.

In the literature some discussions already exist on (i) energy harvesting technologies [19], [21], (ii) available power management mechanisms [87], [74], (iii) the challenges of energy harvesting networks for wireless sensor networks [1] and (iv) existing energy harvesting sensor nodes [2]. However there is a need for the consolidation of new energy harvesting and storage technologies, design principles and recommendations, justifications for the use of energy harvesting in applications, energy harvesting models, protocols for harvesting networks and scheduling algorithms for networks with energy harvesting nodes. In this article, we present a holistic view of the current state of the art research in these areas. The various components of an energy harvesting network that we discuss here can be seen in Fig 1. While some of these have been discussed in part by the above mentioned literature, they have not been discussed before in totality with respect to networks with energy harvesting nodes. This article provides the state of the art as well as direction for future endeavors with energy harvesting networks.

The organization of the paper is as follows: in Section II, the various application areas and the justification for the use of energy harvesting devices in these areas is listed. The sources that can be tapped and technologies that enable energy harvesting are discussed in Section III. An overview of energy storage technologies, their issues and solutions proposed to solve or circumvent these issues form Section IV. A discussion of energy harvesting models that have been proposed in the literature are discussed in Section V. Systems for the efficient extraction and conversion of energy from one or more ambient sources and design recommendations are listed in Section VI. Hardware and software based solutions to energy and power management in harvesting devices are summarized in Section VII. Various protocols for the effective management of a network are covered in Section VIII. Finally, in Section IX some existing issues in energy harvesting system design, networking protocol design and future directions are outlined. We conclude in Section X.

## II. APPLICATIONS OF ENERGY HARVESTING

Energy harvesting is a choice for applications, which require increased lifetime, independence from the batteries and ease

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[1] Reincarnation is an age old concept in Hinduism and Buddhism wherein every living being is born again after its death. One could say something similar about a device operating on harvested energy which has such a never-ending birth and death cycle.

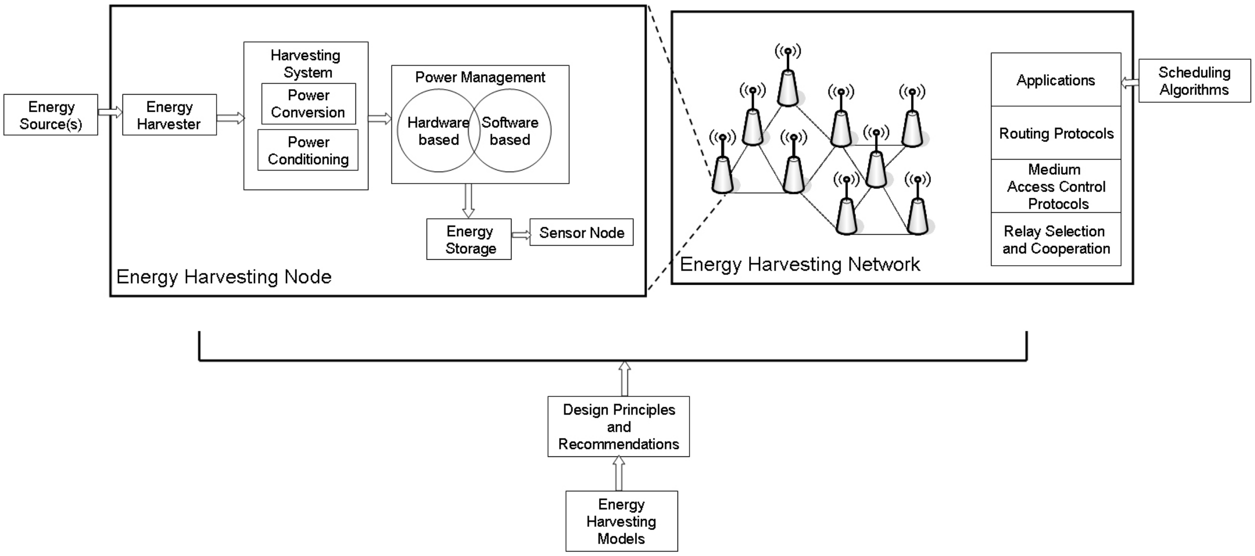


Fig. 1: Components of an Energy Harvesting Network & the Scope of this Survey

of maintenance. It is a means used to improve the life of systems that are currently battery operated. There are many applications and have been discussed in literature often. We list here some interesting applications in which devices are enhanced with energy harvesting solutions. Similar applications and systems for similar scenarios could benefit from the following works.

Describing an aircraft health monitoring system using wireless sensor nodes, Bai et al., [3] outline the possibility of running these nodes with energy harvested from thermoelectric or vibration sources. Nelson et al., [4] present a method to implement power harvesting for monitoring the health of railroad tracks with data from measurements on a real railroad track implementation. Energy harvesting for structural monitoring is discussed by Park et al., [5] and the possibility of wireless energy transfer using RF power is also tested in a similar setting[6].

In body sensor networks, it becomes important for the sensor node to scavenge energy as it is required to be autonomous and must have long lifetimes. Also, biometric sensors are implanted in the body making it impractical to replace the node or energy storage devices. The use of motion based harvesting has been suggested for implanted devices [7] and the use of hybrid scavenging systems of thermal and photovoltaic harvesting has been suggested for wearable devices [8].

On one hand, energy harvesting could be used for applications as mentioned above that employ devices deployed in hard-to-reach areas. On the other hand, it could also be used in applications that simply require too many devices such that the cost of replacing batteries is too much. Electronic shelf-labeling used to display prices of products on shelves is such an application [9]. These shelf labels are capable of updating their displays based on inputs from a server with no other manual intervention. The possibility of powering such shelf label nodes with energy harvested from solar cells is discussed and a prototype design is also described.

Another scenario is where the availability of a steady supply of electricity is not guaranteed. Such an application is discussed by Prabhakar et al., when they describe the use of harvesting to power delay tolerant networks for use in monitoring parameters in an agricultural setting [10].

Finally, energy harvesting could provide some relief on our dependence on fossil fuels and other traditional energy sources. It is suitable for devices that form the “Internet of Things”. With the number of devices per person multiplying rapidly, the use of energy harvesting could be the difference between the proliferation of this trend or its demise with fast depleting traditional energy sources. Similarly it is a good solution for wireless sensor networks in a smart home or office environment, where sensor nodes have to be installed in an old or existing building. Apart from reduction in cost of modification of buildings for wiring purposes and subsequent maintenance, it can be argued that by using harvesting technologies with dense sensor networks, some energy savings can be enjoyed in the long run.

Sensor nodes operating in ambient energy rich environments such as vehicles and industries must capitalize on this available energy. Lindley suggests that waste heat from industry plants can be made to “work twice” [11]. While the scale that Lindley discusses is of the order of megawatts, the philosophy extends to small embedded devices as well. Small amounts of energy from the environment that would otherwise be considered too small to recycle - for cost reasons – would be sufficient to run sensor nodes. Thus the overall energy efficiency of industries and vehicles could be improved. In summary, the advantages of using harvested energy to power small embedded devices are manifold. These advantages are pronounced in wireless networked embedded systems and provide capabilities such as extended lifetimes and autonomous operation. Furthermore, the long-term effects of using ambient energy could have a positive effect on the environment as the need for replacing batteries reduces and dependence on traditional energy sources such as fossil fuels could reduce.

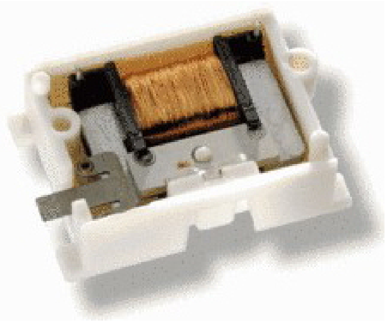
## III. ENERGY HARVESTING TECHNOLOGIES

Energy harvesting technologies are broadly divided as devices that extract energy from incident light, heat, mechanical movement, fluid flow and ambient radiation. Each of these sources has unique properties and is modeled differently. Similarly, the technologies for extraction of energy from these sources have their own peculiarities. The nature of sources and their corresponding harvesting technologies must be studied and characterized well. In order to guarantee sustained operation, it is imperative to choose the best energy harvesting technology based on the application and where it is to be deployed.

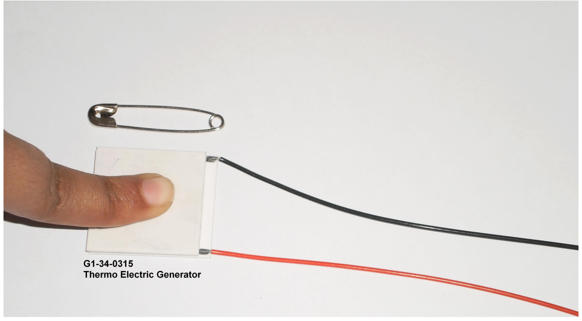
Energy harvesting from photo-voltaic cells is popular and well studied. Dondi et al., present and study a simple equivalent circuit model of a photo-voltaic cell [12]. As an example of how this model could be used, the authors demonstrate its application in finding a system suited for indoor energy harvesting. While photo-voltaic cells are most popular for energy harvesting systems because of the availability of solar irradiation, the efficiency of these cells is poor. Table I lists the reported efficiency numbers of some types of solar cells. In order to improve the efficiency of solar cell harvesting, methods such as maximum power point tracking (MPPT) are popularly used [14], [15], [16]. MPPT circuits operate on the basis of the maximum power transfer theorem to extract as much power as possible by impedance matching, in order to compensate for the varying characteristic resistance of solar panels (due to varying levels of insolation), thus providing higher power outputs. A comprehensive survey and comparison of various MPPT techniques is given by Esram and Chapman [17].

Energy harvested from vibrations is garnering attention from researchers because of its application in structures where vibrations are available in abundance. There are three conversion mechanisms - electromagnetic, electrostatic and piezoelectric. Electromagnetic harvesters work on Faraday's law of induction, exploiting the current that flows due to the relative motion between a coil and a magnet. In electrostatic harvesting, the relative motion between two conductors that form a capacitor is used to generate energy. Piezoelectric harvesters are made of materials that develop a charge when mechanical strain acts on them. Table II compares these conversion mechanisms. Piezoelectric harvesters are offered by several companies like AdaptivEnergy, Smart Material, Perpetuum, Mide Volture and Advanced Cerametrics. Most of these devices promise approximately 10mW at 50Hz vibrations. Such a device from Mide Volture is seen in Fig 2(a). Also human-powered harvesters such as the linear motion harvester (ECO100) from Enocean (Fig 2(b)) extract energy from a button-press action.

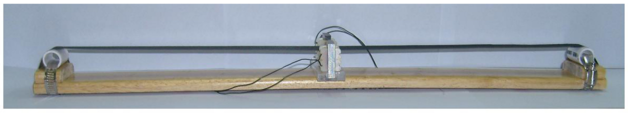
(a) Piezoelectric Harvester



(b) Linear Motion Harvester ECO100



(c) Thermoelectric Generator



(d) Wind Energy Harvester

(e) Hydro Generator

Fig. 2: Commercial Energy Harvesters

In the field of thermal energy harvesting, devices from Micropelt, Enocean and Tellurex are popular among researchers. A thermoelectric generator from Tellurex is seen in Fig 2(c). Energy harvesting from ambient radiation has matured into a commercial product offered by Powercastco. Their product promises energy generation of 10mW at 20dBm of RF at 900MHz. Bouchouicha et al.,[23] present the principle and working schematic diagram of an RF energy harvesting device with the main element being a Rectenna. Their results indicate harvested energy levels of 0.5pW to 100nW at 20 dBm of radiation at 1.8GHz. The authors suggest that an increase in this DC level could be attained by using antenna arrays. Cher

TABLE I: Reported Efficiencies of Photo-voltaic Cells[13]

| Classification | Efficiency(%) | Area (cm$^2$) | V$_{oc}$(V) | J$_{sc}$(mA/cm$^2$) |
|---|---|---|---|---|
| Silicon (crystalline) | 25.0 ± 0.5 | 4.00 (designated illumination area) | 0.706 | 42.7 |
| GaAs (thin film) | 28.3 ± 0.8 | 0.9944 (aperture area) | 1.107 | 29.47 |
| GaInP/GaInAs/Ge (multi-junction) | 34.1 ± 1.2 | 30.17 (total area) | 2.691 | 14.7 |

TABLE II: Comparison of Mechanisms for Harvesting from Vibrations[18]

| Mechanism | Advantages | Disadvantages |
|---|---|---|
| Piezoelectric | No voltage source needed | More difficult to integrate in microsystems |
| Electrostatic | Easier to integrate in microsystems | Separate voltage source needed |
| Electromagnetic | No voltage source needed | Output voltage is 0.1 - 0.2V |

Ming Tan et al., provide a schematic diagram of a circuit that could combine the outputs of such a multiple element array of antennas using voltage doublers and a charge accumulator [24].

Advances have been made in wind energy harvesting that eliminates the need for rotating air-foils. Seen in Fig 2(d), this compact system from Humdinger [22] makes use of a phenomenon known as aero-elastic flutter. The device consists of a 1m×3m×3m stretched membrane that oscillates when there is wind. Energy generated from this movement is of the order of 1 kWh per month for wind speeds of 2 to 12 m/s.

Novel methods such as extraction of energy from fluid motion such as water from a tap are also being considered. Seen in Fig. 2(e) is a hydro generator that can be fixed to a tap. Commercially available harvesters can supply 300mA at 3.6V for a flow pressure of about 0.2mPa [20].

Chalasani and Conrad [19] present a survey of energy harvesting sources suitable for powering small embedded devices. They classify sources as those that generate energy through mechanical vibrations (piezoelectric, electrostatic and electromagnetic devices), light (photo-voltaic cells) and difference in temperature (thermoelectric generators). The authors detail the working principles and technologies of these devices. They also list the advantages and disadvantages of each of these devices. Yildiz [21] provides a compiled comparison of power density and performance of several energy sources (Table III). Yildiz also consolidates the working principles of the devices used for harvesting energy from sources such as mechanical vibrations, solar power, acoustic noise and human power. Also discussed are the working principles of devices such as electromagnetic sources, piezoelectric, electrostatic, thermoelectric, and solar energy harvesting devices. This is effectively summarized in Fig. 3, where, the first of the rows marked with dotted lines classifies the various energy sources in terms of the broad type of technology used, the second row indicates the type of device that is used to harvest energy, and the third row explains the physical principles used for harvesting. We provide an example here on how to interpret the figure. Let us take the example of thermoelectric harvesting. In this harvesting mechanism, energy from the ambiance in the form of thermal energy is harvested. The first block on top explains the technique for harvesting energy i.e., thermoelectric. Following the arrow down to the next block explains one or more methods used to harvest this energy. In this example, it is the use of thermopiles. Again following down to the next block explains the physics behind this harvesting method. Similarly, all types of harvesting has to be viewed in the Fig. 3.

This section provided an overview of different types of energy harvesters, particularly, photo-voltaic, vibration based, thermal, RF, wind and hydro harvesters. This section also summarized the state of the art for each of these harvesters and their achievable power densities. Finally, a concise overview of harvesting techniques and physical principles was presented.

## IV. STORAGE TECHNOLOGIES

Energy storage plays an important role in the energy harvesting. Depending on the level of storage and duration of storage proper storage technique has to be selected. Recently, energy storage devices have evolved vastly. There are several technologies that vary in properties such as energy density, power density, number of charge cycles, leakage, lifetime etc. Due to the wide variations in terms of these properties between technologies, it is important to understand these differences and choose a device that is well-suited for a given application. Here we discuss the general properties of supercapacitor and battery technologies.

### *A. Supercapacitors*

Supercapacitors have been found to be a good choice for use as energy storage or reservoirs because of several reasons. A good idea of the performance of these devices in comparison with ordinary capacitors and batteries can be obtained by studying their position on the Ragone plot [26]. The Ragone plot plots the energy density of energy storage devices against their power density. From the position of an energy storage device on this plot, it is possible to gauge the ability of the device to store energy for long durations of time (high energy density) against their ability to provide a large amount of energy in a short duration when required (high power density). Supercapacitors are placed between capacitors and batteries on the Ragone plot [27], indicating that they have the advantage of higher power density than batteries as well as higher energy

TABLE III: Comparison of Power Density of Energy Harvesting Methods[21]

| **Energy Source** | **Power Density** |
|---|---|
| Acoustic Noise | $0.003\mu W/cm^3$ @ 75dB<br>$0.96\mu W/cm^3$ @ 100dB |
| Temperature Variation | $10\mu W/cm^3$ |
| Ambient Radio Frequency | $1\mu W/cm^2$ |
| Ambient Light | $100mW/cm^2$(direct sun)<br>$100\mu W/cm^2$(illuminated office) |
| Thermoelectric | $60\mu W/cm^2$ |
| Vibration (microgenerator) | $4\mu W/cm^3$ (human motion - Hz)<br>$800\mu W/cm^3$ (machines - kHz) |
| Vibration (piezoelectric) | $200\mu W/cm^3$ |
| Airflow | $1mW/cm^2$ |
| Push buttons | $50\mu J/N$ |
| Shoe Inserts | $330\mu W/cm^3$ |
| Hand generators | $30W/kg$ |
| Heel strike | $7W/cm^2$ |

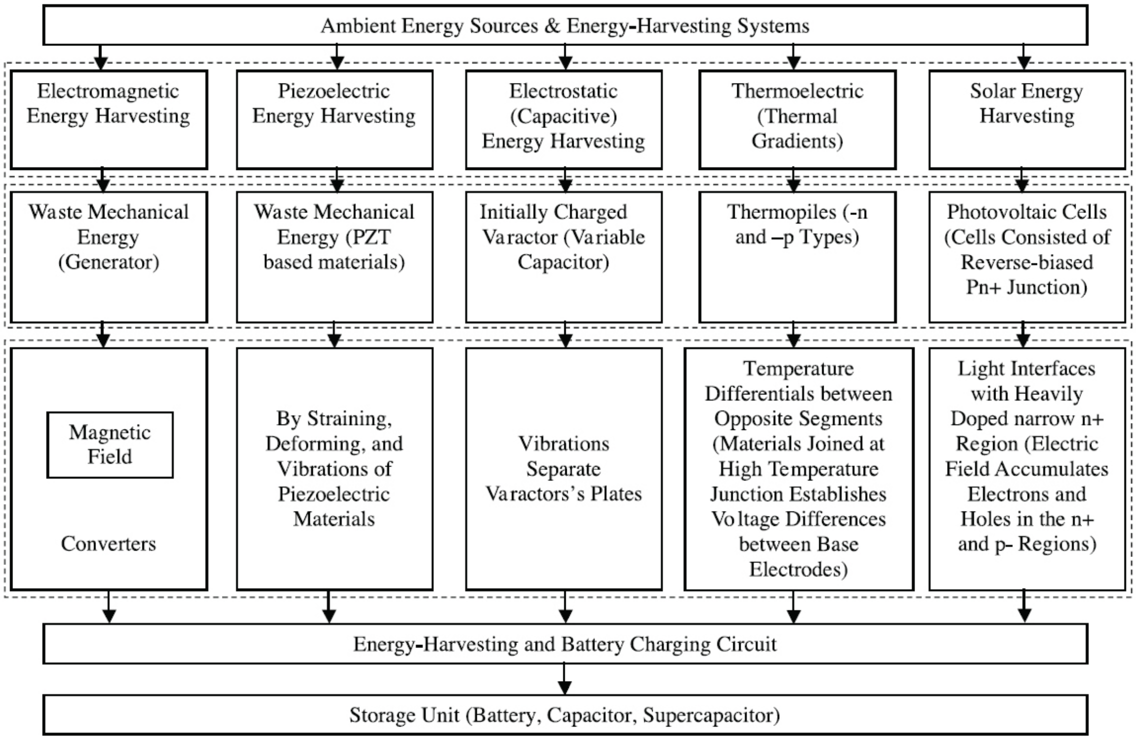


Fig. 3: Summary of Extraction Principles of Energy Harvesting Sources [21]

density than ordinary capacitors [28]. They do not undergo irreversible chemical reactions [31], thus they have of the order of millions of charge cycles [32].

Compared to batteries, supercapacitors have less complex charging circuitry [33], though they do need some smart solutions such as voltage threshold turn-on switch [6] due to the "zero energy bootstrap problem" [34] as demonstrated by Prabhakar et al., [35]. This is caused when the system starts from a total lack of energy; the harvester must generate enough energy and must also have a large enough voltage for the system to operate stably. Another solution would be to use two values of capacitances: a smaller value supercapacitor, which would buffer enough energy to perform a stable "cold boot" and a larger capacitance that would act as the primary energy storage unit [36].

The complexity of the charging circuit could increase if a high capacitance and high voltage rating is expected in an application. The construction of commercial supercapacitors is such that their voltage rating reduces at higher capacitances. To improve voltage rating, it is common practice to connect a string of supercapacitors in series. This practice could result in some units being subject to a voltage higher than their rated value. In such a case, the lifetime of supercapacitors degrades considerably or could even explode. This gives rise to the need for voltage balancing [37] or use of voltage limiting solutions such as Zener diodes [38].

Residual energy in a supercapacitor is easily calculated as $E = CV^2/2$, $E$ being the energy, $C$ the capacitance and $V$ the terminal voltage. Energy consumption for every operation or over a period of time can be simply calculated as $E = C(V_2^2\text{-}V_1^2)/2$, $V_1$ and $V_2$ being the initial and final voltages. This allows for ease of energy measurements in sensor nodes leading to an increased accuracy of energy awareness which forms the basis of several scheduling, routing and management solutions for energy harvesting wireless sensor nodes.

Capacitance of the supercapacitor is an important parameter as the amount of energy that can be accumulated depends on this. The larger the capacitance, the higher the amount of energy will be that can be stored in the supercapacitor. However, it has been found that supercapacitors with larger capacitance undergo larger losses in stored energy due to leakage. Thus a large capacitance supercapacitor not only takes longer to charge, but it also discharges faster. This implies that the number of operations that could be performed at a particular rate is lesser than the number of operations that could be performed when employing a lower value of capacitance, at the same rate. This could lead to scenarios where the rate at which a node performs operations has to be increased in order to be comparable to this number in the lower capacitance scenario as seen in Fig. 4(which is a representation of this phenomenon and does not present experimental results). Choosing too small a value of capacitance would result in the wastage of available ambient energy. So it is wise to choose an appropriate value based on the application's requirements [10] or on the rate of harvested energy [38].

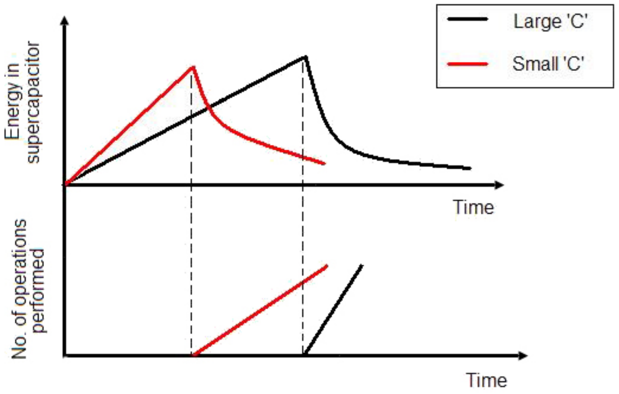


Fig. 4: Comparison of Large and Small Valued Supercapacitors

The major drawback of these devices is the phenomenon known as internal charge redistribution [39] which causes self discharge of up to 10% of the stored energy every day [38]. While there are energy models accounting for this supercapacitor leakage [40], [30], [38], Ting Zhu et al.,[34] propose a scheme in which the node's duty cycle is decided based on lifetimes predicted by knowledge of the leakage in the supercapacitor and harvesting rate. Supercapacitor charging efficiency is extremely high because of low equivalent series resistance (ESR) [41]. Yet, some loss occurs due to this internal charge distribution. Some researchers suggest that loss of charging efficiency due to internal charge distribution can be partially offset if the supercapacitor undergoes more than 3 cycles of a fixed pattern of charging [42]. However, others suggest that leakage is higher in supercapacitors that go through charge cycles too often [86]. Discharging efficiency has been shown to increase with longer discharge times or lower discharge currents [91]. Another drawback of supercapacitors is the effect of elevated temperatures on their ESR and consequently on their lifetime. While measurements indicate that supercapacitor lifetime degrades by a factor of 2 with a $10\,^{\circ}\mathrm{C}$ rise in temperature [43], it has also been shown that the temperature of supercapacitor banks increases exponentially after being charged for a given duration of time at constant current [91].

### B. *Batteries*

In energy harvesting networks, it is common practice to use rechargeable batteries for storing energy owing to their high energy density. However, these devices are losing favor among researchers due to disadvantages such as low lifetimes, low power density and tendency to leak, explode or fail abruptly. Simjee et al., [44] provide a detailed comparison of popular battery technologies including Lithium, Lithium ion and Nickel metal hydride (NiMH) batteries as well as supercapacitors.

With respect to battery charging and lifetimes, Butt and Erickson [45] attempted to answer how much useful energy can be extracted from a battery after charging to a given level. The authors describe a method to test the battery's storage characteristics in which a battery is charged for a given duration of time up to a percentage of rated capacity and allowed to discharge. The discharge is measured by a simple circuit consisting of a voltage comparator, analog switches, resistors and a clock. The authors report the superiority in performance of NiMH batteries over Nickel-Cadmium cells. Finally, lifetime results for batteries charged to 30% and 60% of rated capacity are discussed. The lifetime of batteries appears to be more stable with increasing charging current when they are charged to 60%, but show an upward trend when charged to 30% capacity, indicating that it is beneficial to charge a battery to a larger percentage of its rated capacity. Their results also indicate that there is a small decrease in battery lifetime as the charging current increases.

In traditional energy harvesting system designs, a battery is charged and discharged simultaneously. Alippi et al., [46] suggest that by separating the charging and discharging phases of a battery, it is possible to maintain better control over these individual phases. In order to achieve such separation, they propose a "tandem battery solution" in which batteries are separated from the charging system and from the load using a system of switches such that, while one cell is being charged from a photo-voltaic cell, the other is used to power the load. It is suggested that such a separation could help prevent the deviation from manufacturer specifications that occur in traditional systems. This separation would also mean that partial charge or discharge cycles that are detrimental to battery lifetimes would be prevented.

In certain scenarios it is not advisable to use batteries in energy harvesting applications as they are not capable of dealing with spikes in harvested energy, unlike supercapacitors. Similarly, drawbacks in supercapacitors such as high leakage are not found in batteries. Thus, when an application requires high power density as well as high energy density, it is possible to employ a hybrid of both devices. Jiang et al., [30] present an analytical method to arrive at the optimum capacitance value to use as a primary buffer while a battery was available as a secondary buffer. The secondary buffer was available for use when no harvested energy was available. The calculation considers the leakage from the supercapacitor and level of consumption in the system. Park and Chou [29] propose the use of a reservoir capacitor array to smooth out spikes and wide variations in harvested energy and to protect batteries from undergoing deep discharge thus protecting them from aging effects. Saggini et al., [47] propose the architecture of a power conversion system that aims to exploit the fast charging capabilities of supercapacitors and the energy density of lithium cells. They also introduce a means to calculate the appropriate battery and supercapacitor size to use this in architecture for a given application.

A recent trend in rechargeable battery technology is of solid state thin film batteries. Current commercial offerings from Infinite Power Solutions [48] and Cymbet Corporation [49] provide a choice of batteries that offer operation at 4V and a charging capacity of 0.1 to 2.5 mAh. The extremely small mass of less than 1000mg and thickness of less than 200$\mu$m allows the stacking of these devices to form battery packs of larger capacities. These devices have a life of 5000 to 100,000 cycles. They do not need any specialized charging circuit and can be trickle charged which is an advantage for energy harvesting systems. Manufacturers also promise a self discharge that is lower than that of supercapacitors. Both the above mentioned manufacturers also offer complete energy harvesting solutions that club popular harvesting mechanisms with their batteries.

This section discussed the two important storage technologies used in the energy harvesting systems supercapacitors and batteries. First, the suitability of supercapacitors, their advantages and disadvantages were discussed. A tradeoff between capacitance values and energy storage over time was provided, which should be considered during system design. Next, the usability of rechargeable batteries in energy harvesting systems was discussed. The properties of batteries (e.g., energy density, leakage, recharge cycles) were discussed. Certain design methods when employing batteries were presented, Finally, solid state batteries were presented.

## V. ENERGY HARVESTING MODELS

Modeling of energy harvesting networks is an important activity that is required to understand the challenges, requirements and peculiarities of energy harvesting systems. Abstraction of an energy harvesting system into a generalized model while necessary is tricky because of the variations in energy harvesting profiles and consumption profiles depending on the type of harvesting mechanism, application, network density and several other factors. As a result there are several models in literature that attempt to represent specific types of energy harvesting devices for specific applications.

### *A. Markov Chain Based Models*

Keeping with the highly random nature of these devices, several researchers have proposed modeling energy harvesting with the help of Markov chains. Seyedi and Sikdar[50] attempted to model energy and event-detection traffic in a wireless sensor network running on harvested energy using a 2N-state Markov chain. This 2N-state model includes a 2-state energy harvesting model whose states “active or inactive” represent whether or not energy is being harvested, while event occurrence is modeled by a probability ‘$p$’. The assumptions made are that time is slotted such that energy required for a single event can be harvested in this time slot. The 2N-state model also represents the residual energy in the battery. Thus, each state in the model represents the battery state and also whether there is any harvested energy in that slot of time. A state transition occurs when energy is harvested and/or when an event is detected and communicated. With this model in place, the authors attempt to describe the probability that an event is not detected or reported because the system has run out of energy and the average time taken to reach this state.

Medepally et al., describe a similar model [51]. Here a discrete-time Markov chain is used to represent energy and data traffic in an energy harvesting sensor network, again with the assumption that time is slotted. Each state in the Markov chain represents the amount of energy in the battery in terms of number of transmissions possible as well as whether an acknowledgment has been received from the end node for the previous transmission. The authors present an analysis of communication performance based on the probability that a data packet was not successfully transmitted due to lack of energy or channel conditions. Such an analysis is carried out for an exhaustive set of scenarios: when energy harvested in a time slot is less than, equal to or larger than that required for a transmission, different battery storage capacities, for different probabilities of energy availability in a time slot, and considering for slow or fast fading wireless channels.

Jing Lei et al., [52] use a continuous time Markov chain model the state of the energy storage device and the traffic in an energy harvesting sensor network. It is assumed that energy can be replenished through energy harvesting, replacement of the storage device or a hybrid of both. Depending on the means of replenishment of energy, each state in this birth and death process represents the number of possible unit-energy transmissions. State transitions are represented as the different rates at which energy is harvested, batteries are replaced and at which data traffic is generated, each following an independent Poisson process. This model is further expanded into a Markov decision process in the following way. The authors consider a scenario where each packet to be transmitted has a “message value. This message value has a reward function associated with it. The system is programmed to decide whether a packet must be transmitted based on thresholds set on this reward function. Maximizing the value of this reward is shown to result in an optimal transmission policy.

Describing a model for energy harvesters, Ho et al., [53] present empirical data that suggests that energy harvesting is best described as a non-stationary Markov process. Given that most previous models assume stationary processes, the authors emphasize on the need to create a generalized model to describe such non-stationary processes. To simplify analysis, the generalized model is abstracted as a stationary Markov chain – with the state being the amount of energy harvested, conditioned on another stationary Markov process given by a "scenario" parameter. The model is said to be general since the stationary Markov chain is a special case of this generalized model. The scenario parameter could be the time of day which has a bearing on the energy harvested by a solar harvesting device, the level of windiness in case of wind energy harvesting or simply the harvesting history. In other words, it allows the model to include context. Since the model is only for harvested energy, a state transition occurs only when energy is harvested. The authors describe the means to test the suitability of these models to a particular energy harvesting mechanism using Bayesian Information Criterion. Based on this evaluation, they recommend that the proposed generalized model better describes energy harvesting from vibration while the stationary model is sufficient to describe solar energy harvesting.

On similar lines, in a solar harvesting network, context can be represented in terms of a state diagram as represented in Fig. 5. Each state in Fig. 5 represents a distinct solar condition – in terms of luminous intensity – which could be represented by a discrete harvested energy level depending on the size of the photo-voltaic cell. Such a state diagram could be derived from past history at each node to define the state transition probabilities, or defined at design time by an off-line measurement. These transition probability values could be used by the node to predict the rate of harvested energy or to record context.

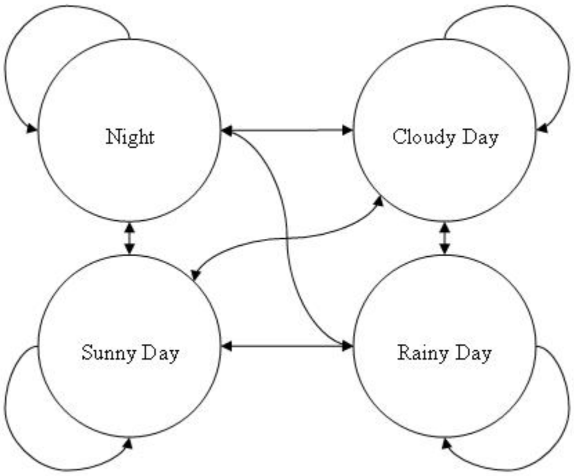


Fig. 5: State Diagram for Solar Conditions

Attempting to arrive at an accurate model for harvested energy through a curve fitting approach, Lee et al., [54] present goodness-of-fit results of different statistical models to empirical data. Once again time is assumed to be divided into slots. Further, it is assumed that the energy harvesting node transmits in a slot only if energy is available in the buffer at the start of that slot. The authors model the number of time slots in which no energy is available for transmission, with several distributions: discrete uniform, geometric, Poisson, and transformed versions of geometric and Poisson. They also consider a 2-state Markov chain where the states represent whether or not energy was harvested in the last time slot. These different statistical models are then compared to the number of measured no-energy slots in a controlled solar energy harvesting environment. It is found that a Poisson distribution with an arbitrary transformation best matches measured data.

### B. Miscellaneous Models

Other approaches to modeling energy harvesting systems aim at providing design-time recommendations. Kansal et al., describe a leaky bucket model [55] that is similar to the popular token bucket model used in queuing systems, which applies a maximum flow constraint on incoming energy. The philosophy behind such a constraint is to model the capacity of an energy storage device. Further, unlike the Internet model, they also introduce a minimum flow constraint to illustrate that some energy from the energy storage devices remains unusable in practice. For example, energy in a super-capacitor is unusable if its voltage level is not sufficient to run the sensor node. These flow constraints in combination with the power consumption profile of the consumer can then be used to decide the size of the energy storage device and the capacity of the energy harvester in terms of instantaneous power. A design made with these considerations can then be expected to sustain operation to eternity.

Niyato et al., describe a composite model [56] that includes a Nakagami-m fading wireless channel, a solar radiation model from [57], a photo-voltaic cell and battery model to represent the wireless and energy conditions of a solar energy harvesting sensor or mesh node. The sensor node is modeled as a queuing system that has two input traffic flows – one generated locally and the other arriving from neighboring nodes. The packet arrival process is modeled as a batch Markov arrival process in order to factor the burstiness of traffic. The state space of this composite model includes the number of packets in the queue, packet arrival state, the channel state, the battery state, the state of solar radiation and the sleep state of the node. This model is then used to derive performance measures such as packet dropping and blocking probability, sleep probability, average values of delay and queue length, queue throughput and average battery capacity.

Hormann et al., [58] describe a nested tier model of energy harvesting system functionality. The five tiers in this model (Fig. 6) represent blocks of the energy harvesting power-train: the energy storage tier, the storage access tier, the power control and conditioning tier and the device measurement tier. Each tier consists of an input and output module and interaction between these tiers indicates a flow of energy from the output of one to the input of the next tier. There is also a

TABLE IV: Energy Harvesting Models Summary

| Model | Basis | Parameters Modeled | Purpose |
|---|---|---|---|
| Seyedi [50] | Discrete-time Markov chain | Event detection & Incoming Energy | To understand system parameter relationships & to set requirements |
| Medepally [51] | Discrete-time Markov chain | Battery state & Traffic | Performance analysis & reduction of outage probability |
| Jing Lei [52] | Continuous time Markov chain | Battery state & Traffic | To derive optimal transmission policies |
| Ho [53] | Discrete-time Markov chain | Incoming energy | To model energy accurately |
| Lee [54] | Various models | Time slots with no energy harvested | To find the best energy model |
| Kansal [55] | Leaky bucket model | Flow of energy | To demonstrate energy neutral operation |
| Niyato [56] | Composite of several models | Entire energy harvesting system | To derive performance measures & arrive at optimal sleep strategies |
| Hormann [58] | Tiered model | Harvesting system function | To provide design recommendations |
| Ozel [59] | AWGN channel | Transmission between energy harvesting nodes | To derive the capacity of the channel as a function of harvested energy |
| De Mil [60] | Virtual capacitor | Flow of energy | To provide an implementable means of tracking energy flow |

flow of information and control between tiers that is used for supporting energy and power aware operation. The absence of these flows would indicate a "fixed" module. This model provides designers with recommendations on what elements would be required in a harvesting system given the application's needs. Also, given a "fixed" energy harvesting system, the tier model could be used to understand how efficiency of operation could be enhanced. This is possible because the interaction between tiers is well defined in a simple manner. In a different take on modeling of energy harvesting systems, Ozel and Ulukus [59] represent the communication process between an energy harvesting transmitter and a receiver as an AWGN channel with random energy harvesting to be stored in an energy buffer. The authors liken the randomness of energy harvested to that of fading channels, with the difference that energy can be stored. This major difference allows a margin, without which the instantaneous quality of communication would be affected. The authors define the capacity of this AWGN channel as a function of the average power harvested.

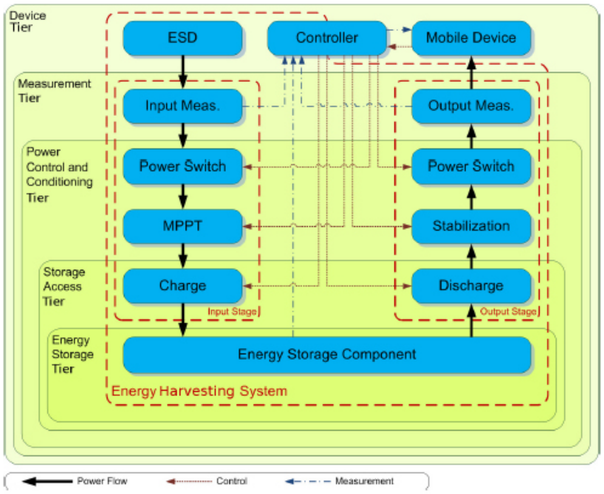


Fig. 6: Five Tier Model of an Energy Harvesting Node [58]

Finally, De Mil et al., [60] provide an easy-to-implement model of an energy storage device in a harvesting system. This model can be described as a 'virtual capacitor' whose voltage level is a function of the integral of difference between harvested and consumed current, the equivalent capacitance of this capacitor being a function of the rate at which these two currents are measured. The authors intend to use this model as a means of keeping track of energy in the harvesting system in order to perform energy aware operation.

This section presented an overview of efforts in modeling energy harvesting systems. The proposed Markov chain models and other Markov chain based models for energy harvesting systems were presented. Several works on source modeling based on Markov chain and curve fitting were described, and our proposed 4-state model was also described. Models of energy harvesting system not based on Markov chains like leaky bucket etc., were presented. While most of these models have been proposed to evaluate the performance, one model has been proposed in the literature for design recommendations. A summary of all models discussed here is presented in a concise form in Table IV.

## VI. ENERGY HARVESTING SYSTEM DESIGN

In this section we discuss hardware that converts harvested energy into a usable form suitable to the application. There are several requirements for such hardware. Energy harvesting systems are required to be very efficient, considering that ambient energy is available in minuscule amounts. Harvesting systems must be robust and reliable as they are ideally expected to last for a long time. These requirements have been shown to be achieved when energy harvesting hardware is adapted to the harvesting technology used, the storage technology used and the application itself. A concise summary of discussed energy harvesting systems is presented in Table V.

### A. *Harvesting Technology Specific Design*

Nuffer and Bein [25] delve into the details of piezoelectric materials and their applications in energy harvesting apart from

TABLE V: Comparison of Energy Harvesting Systems

| System Name | Harvester Source | Storage Technology | Control | Energy Performance |
|---|---|---|---|---|
| Thermal system from Becker &others [65] | Thermal difference | Supercapacitor | PFM Controller in DC-DC Converter | 85 % (Depends on efficiency of DC-DC Converter) |
| Alippi et al., MPPT design [67] | Solar Energy | 300mAh NiMH battery | Dedicated CPU | Less than 1mW |
| Heliomote [62] | Solar Energy | 2 NiMH cells | Software driver on sensor node's MCU | 80 - 84% efficiency |
| Everlast [33] | Solar Energy | Supercapacitor | MPPT controller on sensor node's MCU | Efficiency varies depending on operating voltage & supercapacitor size |
| Prometheus [30] | Solar Energy | 22F Supercapacitor + 200mAh Lithium battery | Software driver on sensor node's MCU | Consumes 205$\mu$A with Telos node @ 1% duty cycle |
| Ambimax [29] | Solar Energy + Wind Energy | Supercapacitor array + 1 cell Li-ion/Polymer or 2 AA type | Entirely Analog | Consumes 500$\mu$A @3.3V |
| PUMA [70] | Solar Energy (expandable to other sources) | Li-Polymer Battery | Dedicated MCU & switch array circuit | Extracts 33% more energy<br>Consumes 9.92KJ less |

their use as sensors, actuators and transducers. The authors present results that suggest that the piezoelectric material must not be studied independent of the energy storage mechanism itself. The method of energy extraction is shown to have a bearing on the degradation of the piezoelectric material. This indicates that attention must be paid to the design or choice of the system with respect to the harvester and vice versa. Here, we provide an overview of systems designed to extract energy from a specific harvesting source.

On the subject of thermal energy harvesting, Becker et al., [65] describe the circuitry required for efficient extraction of energy from difference in temperature using COTS thermoelectric generators. This system design requires the use of a DC-DC converter that is started with the help of a charge pump, load matching for maximum extraction of power from the harvester and the use of only a supercapacitor for energy storage. The authors advise that since the efficiency of power conversion is dominated by the efficiency of the DC-DC converter, it is important to choose the right converter for the design.

In their description of a solar energy harvesting system - 'Heliomote' [62], Raghunathan et al., make the following contributions: (1) description of the impact of various considerations and trade-offs in the design of a solar harvesting module, (2) desired features of a solar harvesting module, (3) services the harvesting module should provide to the rest of the system to improve power management, (4) describe harvesting aware power management, (5) performance evaluation of 'Heliomote' and demonstration of the feasibility of solar harvesting for WSNs.

Alippi and Galperti [67] describe a new system for design of MPPT system for solar harvesting that adapts to any solar panel size. They describe practical implementation and test this system to run Mica2 motes. This MPPT system uses an adaptive digital control loop to keep panel working at the optimal point and a voltage controllable power converter to adapt solar cell with battery. Comparison of this system with the working of Heliomote can also be found in [67]. Arms et al., [61] present details on running sensor nodes using a solar energy harvester and a vibration energy harvester on custom built hardware. They describe power reduction strategies for sensing elements and wireless transceiver elements.

## B. *Storage Technology Specific Design*

The differences in the properties of various storage technologies – discussed in Section IV – require that energy harvesting hardware is adapted to a storage device. Summarized here are some designs that were made with a particular storage device in mind.

Everlast[33] aims to eliminate batteries in wireless sensor networks and replace them by supercapacitors, for their long life, low ESR and leakage currents, thus making nodes that would last for 20 years. This hardware performs MPPT using a feed-forward pulse frequency modulated converter. Everlast is used to power a custom built sensor node.

Prometheus[30] is a system designed with a primary energy buffer - a supercapacitor and a secondary buffer - a rechargeable Lithium battery that could be charged with solar power. This system is assisted by software that switches between the primary and secondary buffer depending on the availability of solar energy. The authors give recommendations on how to choose the size of a solar panel for a system and how to model the system's power consumption depending on the node's duty cycle, active sleep current and supply voltage. Further, the primary buffer (supercapacitor) is modeled as an energy source. The leakage of the supercapacitor and the consumption by the load are also incorporated in this model. Through such a model, the authors are able to provide directions on the choice of supercapacitor value corresponding to the expected duty cycle of operation of the load and current drawn during active and sleep states . Trio [68] is a combination of a computation and communication device - Telos mote, a sensor and timer module - XSM and a power harvesting & management module - Prometheus. The criteria used to choose these circuit boards for their deployment experiment - sustainability, flexibility and fail-safe operation. Packaging details and issues with the deployment of a large scale deployment of several hundred nodes such as protocol failures, loss of data due to power instability are also discussed. The authors stress the importance of the integration of harvesting and communication hardware as well as software for large-scale deployments.

### *C. Harvesting System Design for Multiple Sources*

Ambimax [29] is an analog architecture for efficient, autonomous extraction of energy from multiple sources simultaneously. This is achieved by a specially designed harvesting system that consists of a reservoir capacitor array, an MPPT circuit and a PWM regulator for every individual source. Each of these subsystems is adapted to the harvesting source. The capacitor array is used to smooth out spikes thus slowing battery aging and resolving an imbalance between power generation and consumption. The MPPT circuit is free of any digital control as it uses special sensors to derive information on the power sources. The output of each of these subsystems is given to the control and charging system which consists of battery charging and protecting circuitry. As each harvesting source has its own harvesting subsystem – strung together, various harvesting systems can be used at the same time to power a single device.

PUMA [70] attempts to solve the problem of matching consumption to the available power. A major problem with harvesting systems is identified as the fact that batteries cannot be charged and discharged at the same time. This is because if the ambient power is not at least enough to drive the system, battery power must be used. Thus, available ambient power below a threshold is wasted. PUMA is used to power "Duranode" a wireless sensor node that is divided into subsystems – a wireless communication subsystem, a microcontroller subsystem, a sensor subsystem and a battery charging subsystem. PUMA uses a set of power source sensors to determine the amount of ambient power from wind energy generators or solar panels etc., and uses a controller to decide based on an algorithm or a lookup table, what subsystems can be powered with the available energy. These subsystems are then powered up using a switch array. Thus power from various sources can be matched to the power requirement of various consumer subsystems.

This section first summarized the works on harvesting technologies, mainly piezo, thermal and solar harvesters. This section described certain implemented energy harvesting system with specific choices of harvester and storage. This is summarized in Table V.

## VII. ENERGY/POWER MANAGEMENT FOR ENERGY HARVESTED WSNS

While the main concern of most battery-powered sensor networks is to extend network lifetime to as long as possible, energy harvesting networks do not suffer from an energy shortage. The perpetual availability of energy in energy harvesting networks is one of the reasons why these are attractive to researchers. While such eternal availability of energy can be counted on, there are limitations on instantaneous power availability related to the application and the requirements of the hardware in use. This instantaneous power capability of the harvesting element is limited by parameters such as size, weight and cost. Hence, it is important for harvesting nodes to ration and manage power. Also, most energy harvesting node designs are not efficient in conditions of cold-start. This makes it important to manage energy as well to avoid nodes from dying due to depletion of energy, even if energy is freely available in the long run.

### *A. Software-based Solutions*

*1) Harvesting-aware Power Management Strategies:* Several suggestions have been made to improve usage efficiency and management of power and energy. Pimentel and Musilek provide a survey of power management strategies [87] in energy harvesting devices. These include strategies for every module in an energy harvesting system and are listed in Table VI. The authors list the various blocks (perspective) in a harvesting system and discuss the available software-based strategies that may be adopted in that block for optimum power management. For example, at a system level, duty cycling is a technique amongst others listed in the table. Similarly, at the peripherals and sensors one can manage the available power by adapting the way sensing is done. At the transceivers (or networking) we may use compressed data and optimum power usage for the particular scenario at hand, for example event driven strategy. While the Table VI provides some commonly used strategies, we believe that there are many such techniques and strategies that are being evaluated and reported.

While the strategies listed in Table VI are to be implemented in an existing harvesting system, Kansal et al., [92] discuss strategies for every aspect of an energy harvesting sensor network. They begin with recommendations to hardware designers on efficiency at the various stages of harvesting, storing and utilizing energy. These include the proper modeling of the harvesting element, choice of the correct MPPT technique, choice of battery type and size to reduce loss of efficiency due to wastage. They suggest that designing a harvesting module specific to the application and harvesting source would go a long way in improving efficiency. Additionally, they underscore the need for power management at the sensor node which consists of the use of schemes that are aware of the rate of harvesting and the residual energy and scale performance based on these details.

*2) Adaptation for energy-neutral operation:* The popular focus of most energy harvesting research is to enable sustainable operation to eternity at a desired performance level. Kansal et al., [89] suggest that this could be achieved in two ways: (a) by applying power management techniques used in battery operated systems to maximize lifetime or (b) by operating at a rate that is always less than the rate of harvesting. The latter approach termed as energy neutral operation is achieved by adapting the duty cycle of operation

TABLE VI: Harvesting Aware Power Management Strategies [87]

| Perspective | Strategy |
|---|---|
| System | Duty cycling<br>Adaptive duty cycling<br>Dynamic voltage scaling(DVS)<br>Dynamic frequency scaling (DFS)<br>Dynamic voltage and frequency scaling (DVFS)<br>Maximum power point tracking |
| Peripherals | Adaptive sensing rate<br>Adaptive memory management |
| Sensors | Turn on power to the sensor only when sampling.<br>Turn on power to the signal conditioning only when sampling a sensor.<br>Sample the sensor(s) only on event.<br>Reduce the sensor sample rate to the minimum required by the application.<br>Sleep between samples.<br>Scalable fidelity. |
| RF transceivers | Reduce the amount of wireless data transmitted through data compression or reduction.<br>Lower the transceiver duty cycle and frequency of data transmissions.<br>Implement strict power management - use power down and sleep modes.<br>Implement an event-driven transmission strategy - transmit only on sensor event(s). |

to the predicted rate of harvest. The authors describe the adaptation of duty cycle as an optimization problem for which a low complexity solution is also provided. Niyato and others [90] solve this problem as an optimal sleep and wakeup strategy with a game theoretic solution.

In a theoretical framework [71], Murthy suggests that given time-slotted operation, energy neutral operation depends on four parameters: (i) the energy that is harvested in a slot, (ii) the maximum energy that is allowed for a single packet transmission by the hardware or power constraints (iii) the average data rate and (iv) the efficiency of battery storage. Thus perennial operation is assured by choosing the fourth parameter if the other three are already known or fixed. Effectively, this theoretical framework refers to the use of power control in an energy harvesting framework. Tan and others [72] present details of their performance analysis on an energy harvesting system where such power control is performed.

Moser et al., describe a scheme in which sensing and communication rates are adapted to the rate of harvested energy while ensuring that memory use is at an optimum level [69]. Such an adaptation is performed by means of linear programming. It is suggested that an application running on an energy harvested node consists of several tasks activated by each other at a certain rate. The authors propose that these activation rates are linearly related to the rate of sensing or communication. An algorithm for the optimization of the sensing or communication rate with respect to the predicted and measured rate of harvested energy and local memory usage is presented.

Prabhakar et al., describe a decision engine [75] that uses (i) the knowledge of the energy consumed by the hardware for each operation (such as transmission, computation, reception etc.) performed by the sensor node, (ii) inputs from an energy prediction algorithm (iii) and a set of heuristic rules to modify an existing application. Such a modified application allows for maximizing the number of operations that can be performed with the available energy.

*3) Energy Measurement and Prediction Mechanisms:* Clearly, it is beneficial to have knowledge of the energy harvested in a period of time. While energy measurements are accurate, they are usually energy expensive and require additional hardware. Dutta et al., describe a simple energy metering design - iCount, that measures energy by simply counting the cycles of the switching regulator employed in the existing power conversion circuit [66]. Since this requires nothing other than a digital counter, hardware costs and energy consumption is minimal.

As we have seen, energy predictions equip the harvesting node to adapt better to future energy availability. The benefits of using energy prediction schemes can be used for improving networking protocols and scheduling algorithms as well. The proposed Weather-Conditioned Moving Average scheme (WCMA) [88] for improved prediction in solar harvesting systems improves on the popular exponentially weighted moving average (EWMA) scheme. EWMA prediction is performed by calculating a moving average of measured values that are weighted such that recent measurements carry a higher bearing on the predicted value. The weights are either arbitrarily assigned or assigned at design time depending on off-line measurements. WCMA, on the other hand, assigns weights that are derived at run time depending on the season and current weather conditions. Bergonzini et al., compare prediction schemes for solar energy harvesting including the WCMA, the EWMA, a novel neural network based prediction scheme and their proposed “ETHZ” predictor that is similar in principle to WCMA [73]. Their results indicate that the neural network scheme has the highest computational complexity and also the highest average error percentage. EWMA performs better in terms of complexity, time for prediction and has the lowest memory footprint, but WCMA allows for the least average error.

### B. Hardware-based Solutions

Several hardware based solutions attempt to solve the problem of energy management. The design of an energy management unit as a singular solution for (i) photo-voltaic energy conversion, (ii) storage, (iii) maximum power point tracking (MPPT), (iv) recycling of energy and (v) dynamic voltage scaling is described by Sankman et al., [85]. Such a solution, aimed specifically at solar harvesting nodes that use supercapacitors as storage units, is meant to provide a complete solution that is also miniaturized to suit the needs of most energy harvesting wireless sensor nodes.

An overview of hardware solutions for power management is provided by Chapman [63], where the author discusses important problems with power management circuitry that use boost converters in energy harvesting devices. The physical size of the inductors used in these boost converters is proportional to the square of the current through it. Thus, as the current increases, the physical size must increase; but as the current increases the input voltage must reduce along with the efficiency of this design. Hence a trade-off exists between physical size and efficiency in such energy harvesting systems. The author expands on the means of operating the power management circuitry at its point of highest efficiency. It is suggested that energy is stored in a storage device and fed to the harvesting node in bursts during which the power converter is always at its highest operating point.

Raghunathan and Chou discuss issues in system design as well as power management in energy harvesting system [74]. The application of MPPT in AC and DC systems using hardware or software controllers is also described. Relating to large losses of efficiency due to MPPT, the authors suggest using a system that is divided into blocks, combinations of which are powered depending on how much power is available such as PUMA [70].

Power management is the crux of the energy harvesting systems, since it enables the extension of node and network lifetime, despite limitations on instantaneously harvested power. In this section, we overviewed the various degrees of freedom, used in several works, that can be controlled at different layers. Several strategies and adaptations for energy neutral operation were also described. Energy prediction is an important component of power management techniques. Several works that predict sources were summarized. Apart from software based solutions, several hardware based solutions were also described.

## VIII. PROTOCOLS FOR ENERGY HARVESTED WSNS

Common issues in wireless sensor networks relating to data transfer include synchronization overheads, the funneling effect [94], noisy environments, adverse effects to network connectivity or frequent changes in routes because of node death due to hardware failure or spent batteries etc. In energy harvesting networks, some of these issues escalate due to a varying energy profile. There are some more scenarios when nodes could die suddenly. For example, this could be caused by an energy harvester with a faulty design. Another example is when light is obstructed by unforeseen changes (fallen tree, new building, etc.) in the physical environment such that solar harvesting nodes in that area are no longer active. Network connectivity suffers greatly. Clearly, energy harvesting networks cannot be completely rid of such issues. If a lifetime extended over decades is to be achieved it is vital that network protocols equip energy harvesting networks to deal with the effect of the energy profile and if possible the above mentioned contingencies. Protocols written for battery driven networks are inadequate in this sense. Hence protocols must be written especially for energy harvesting networks. Seah and others [96] discuss some interesting challenges and open issues relating to protocols for energy harvesting networks.

### A. Medium Access Control Protocols

In energy harvesting networks, requirements of a MAC protocol such as fairness, latency, efficiency and reliability take on additional meaning. For example, a protocol that does not provide true fairness with low delay and energy overhead could cause high loss of network connectivity due to additional energy expenditure in some nodes. In a network that has to deal with fluctuating energy availability, reliability of the protocol could go a long way in providing much needed stability. Here we discuss some MAC protocols specific to energy harvesting networks.

A comparison of several MAC schemes for performance metrics of network throughput, fairness index, and inter-arrival times can be found in [95]. The MAC schemes considered are slotted and unslotted CSMA, identity polling, optimal polling as well as a scheme known as probabilistic polling newly proposed by Eu et al., [95]. This new polling scheme is described as follows: the sink node in a network polls each node in the network based on a “contention probability”. If there is no contention or lack of energy, the node responds in a stipulated time to this polling packet. If a favorable response is received at the sink, the contention probability is reduced. If no such response is received, the contention probability is increased. In this manner, the protocol is able to adjust to collision and node failures due to changes in the rate of energy harvesting as well. The authors show that their probabilistic polling scheme is superior to other schemes in an energy harvesting network as it gives high throughput, fairness with low inter-arrival times, and it is scalable with network size.

In an endeavor to propose a stack for energy harvesting wireless sensor nodes Glatz et al., suggest a cross-layer approach [76]. Their recommendations include a scheme that uses synchronized duty cycling adaptation using a scheme involving sync messages piggybacked with networking messages. Such a scheme is shown to improve the efficiency of the system due to reduced overhead for control messages otherwise needed for synchronization. They discuss the use of network coding over routing specifically for energy harvesting networks, but do not integrate network coding with synchronized duty cycle adaptation due to loss of scalability.

### B. Routing Protocols

Minimum energy routing, residual energy aware routing and energy efficient routing have been discussed extensively and frequently for battery driven networks. Changing energy profiles in energy harvesting networks require harvesting aware schemes and schemes based on energy predictions.

In networks consisting of both battery powered and solar energy harvesting nodes, solar-aware routing schemes are proposed by Voigt et al., [77] that build on the existing directed diffusion method [64] such that positive reinforcement is used to direct nodes to use a path consisting of as many solar-powered nodes as possible. Two variations of this scheme are exhibited: the decision to use a route could be up to a node or it could be based on a route-wide gradient. Such schemes are expected to reduce the load on battery powered nodes in the network thus improving network lifetime. Similarly, in their work on clustering schemes, Voigt et al., [78] introduce a solar-aware clustering scheme based on "LEACH". Since cluster-heads spend more energy than other nodes in a network, it is suggested that the clustering algorithm must choose nodes located physically close and that have the highest energy availability to become cluster-heads. Such a scheme is evaluated against the standard LEACH and shown to be an improvement in terms of network lifetime.

Energy aware routing in low-energy networks is discussed by Shah et al., [79]. While the proposed reactive protocol discussed is meant primarily for battery-powered networks, the concept could be extended to energy harvesting networks as well. The protocol states that each node decides the next hop towards the destination based on a probability which is inversely proportional to a cost factor. This cost factor depends on the residual energy at the node. The authors use this probabilistic selection of next hop nodes to diversify the load on nodes. Thus this scheme is expected not to overly burden a particular set of nodes and it is expected that the network as a whole survives longer without loss of connectivity.

Kansal and Srivastava [93] propose a framework for network-wide energy usage and management, where the underlying idea is to align energy consumption in the entire network with energy availability considering for variations of energy over space and time. In order to do this, a cost parameter is estimated from parameters such as energy consumption, battery residual energy, battery size, predicted values of harvested energy etc. Once this cost parameter has been calculated, it can be exchanged between nodes in the network to make global decisions for purposes of routing, topology management, load balancing, and transmission power control and so on. In this manner, it is possible to perform pertinent modifications to existing tried and tested algorithms to adapt them to energy harvesting networks. As an example, an existing residual energy routing scheme originally proposed by Singh et al., [80] is modified such that it uses their newly devised cost parameter as a metric. The results indicate that using such a modified scheme allows for considerable lifetime improvement over the residual energy scheme.

Lattanzi et al., introduce a metric that is used to test the suitability of routing protocols for energy harvesting WSNs [97]. This metric termed maximum energetically sustainable workload (MESW) that defines whether or not a routing protocol allows for an eternal life. If a node in the network has enough energy to execute a workload, this workload is termed as energetically sustainable. Given that a node has a workload that is energetically sustainable, the MESW parameter refers to the maximum workload (in terms of number of packets delivered to the sink node per unit time) that can be sustained in each node without compromising the sustainability of another node in the network. The authors contend that testing various routing protocols using this metric could allow the selection of a routing protocol that would ensure an increased workload (here throughput) while maintaining network connectivity.

### *C. Relay Selection and Cooperative Communication*

Medepally and Mehta discuss relay selection in a network consisting of relays powered by harvested energy [81]. The source and destination nodes are battery powered. The use of energy harvesting nodes for the purpose of relaying data provides the advantage of perpetual operation achieved through the principle of energy neutrality. The authors present an analytic method to arrive at the optimum transmit power to be used by relay nodes in order to minimize the symbol error rate. The best relay is one that minimizes the symbol error rate by maximizing the SNR over the entire path from source to destination.

Network throughput maximization through cooperative communication is discussed by Tacca et al., [82]. They describe an ARQ scheme where relay nodes, rather than the source, retransmit a packet till it is successfully delivered. The advantages of this scheme include load sharing across the network due to cooperation, spatial diversity and a reduction in energy spent for transmission.

### *D. Scheduling Algorithms for Energy Harvesting Networks*

Scheduling algorithms for energy harvesting nodes must solve a two-dimensional problem. There exists a delicate trade-off between energy opportunity and delay constraints in a node. Moser et al., argue that conventional scheduling algorithms that do not consider energy availability cannot be used here. They propose a "lazy-scheduling" algorithm [83] that uses knowledge from energy prediction to decide which task can be performed now and which can be performed at a later time. By using such a scheme, the node avoids spending all its energy on a task simply because it has an early deadline. Instead, the scheduler delays a task $i$ to perform a task $j$ when energy is available for the latter currently and will be available for the former after some time. The algorithm includes rules such that deadlines are not violated. From optimality proofs of this algorithm, the authors conclude that the lazy scheduling algorithm forms the lower bound for all scheduling algorithms in terms of missed deadlines.

Liu et al., assume a basic algorithm that assigns higher priorities to tasks with an early deadline and modify it such that it discards tasks for which it does not have enough energy [84]. This scheme is combined with a dynamic voltage and frequency selection (DVFS) policy used to deal with instantaneous power and timing constraints. This algorithm is found to decrease the rate at which task deadlines are missed.

Due to the varying energy harvested and other system components, protocols at various layers need to be revisited. This section summarized MAC protocols and routing protocols for energy harvesting networks and protocols of sensor networks that were adapted for energy harvesting networks. Works on relay selection were described. Scheduling algorithms, also an important component of the energy harvesting system, that are proposed for energy harvesting systems were also summarized.

## IX. OPEN ISSUES IN ENERGY HARVESTED WSNS

At the end of this discussion it is important to note some of the aspects that are hindering the wide spread use of energy harvesting. Mainly the form factor of the harvesting instruments is an issue. This makes the instruments bulky and thus it is difficult to build devices which could be easily deployed. Further, the nature of the availability of energy from renewable sources, which provide energy in a fluctuating and intermittent manner, puts stress on the communication protocols aspects. Also, the amount of energy harvested is not usually sufficient for the devices to carry out all the tasks. Thus it is a challenge to deploy the energy harvested devices in large scale at this time. It is expected that advancements in miniaturization and ultra low power chipsets will drive the wide acceptance of the energy harvesting paradigm. On this positive note, we shall discuss several challenges and interesting issues that need to be addressed. We have compiled a list of some of these interesting issues.

- Multi-hop communication in energy harvesting networks is a complex issue due to the unpredictability introduced by energy fluctuations. It is exacerbated in applications that make use of extremely low power and complexity devices that are equipped with very small or no energy storage units. Given this scenario, synchronization is a costly overhead. Low power listening techniques are often not implementable due to complexity. Due to the need for power conservation it is not possible to perform long range communication to avoid multi-hop communication. For the same reason it is also not possible to reduce sleep times. Resorting to means such as increasing node density appears as a superficial solution likely to worsen the situation. Clever mechanisms such as the wake-up radio could be a way forward but spatial variations in energy profile prove to be a hindrance. It must be stressed that in energy-rich environments these issues exist but are not as dire.
- Networks deployed in environments with huge swings in energy availability with time and space, routing in energy harvesting networks faces issues - similar to that of mobile ad-hoc networks - of highly dynamic routes. However, their “reincarnation” capabilities may allow for routing schemes that can combine the advantages of on-demand and table-based routing schemes.
- It is important to have the means to arrive at the minimum density of nodes required for reliable and fault-tolerant operations in energy harvesting networks. Also to be explored would be the maximum delay introduced in such networks for transfer of sensed data and actuator signaling vis-á-vis density.
- The primary application for energy harvesting is in networks that require perpetual operation. Such a requirement raises questions about the minimum required harvested energy injection rate for perpetual operation.
- Performance parameters such as maximum packet drop and maximum information exchange per node per Joule of harvested energy, network-wide throughput and QoS need to be analyzed and studied. The effect of node and energy heterogeneity in the network on these parameters is also to be studied.
- Traditional sensor networks work on event triggered or periodic action paradigms. In the context of an energy harvesting network it might be wise to think in terms of an energy triggered system. For example, in such a paradigm, a node could remain in its sleep state until the energy in its storage unit is above a threshold. Such a system would do away with the need for periodic wake-up to check for energy availability, resulting in energy savings. Furthermore, energy wastage due to the “zero energy bootstrap problem” (see Section IV-A) can be eliminated.
- The possibility of operating wireless sensor and actuator networks on harvested energy has not generated much interest among researchers. This could be caused by the insufficiency of existing harvesting technologies in terms of efficiency and energy density for the purposes of actuation. Energy harvesting technologies can double as environment or context sensors. An obvious example is that of an energy harvesting node equipped with a solar panel or a wind harvester could be used to derive the solar condition or wind speed respectively. Context allows for more intricate applications in a home setting, for instance. With knowledge of the solar condition, an energy harvesting sensor-actuator network could provide energy savings by adjusting lighting or heating inside a building.
- A unifying model for traffic and energy that could be used to design a network that is adapted to all the issues discussed above is much needed. Such a model must represent all the aspects of the energy harvesting system (Fig 1) and their interdependence. Such a model could be used to develop a dedicated simulation tool that is currently unavailable to the best of our knowledge. Extending this tool to simulate wireless sensor and actuator networks running on harvested energy could be the next step. Databases of energy measurements from energy sources are available (e.g. CONFRRM). These databases could be used to aid such a simulation tool.
- Pelissier et al., describe a security algorithm for energy harvesting networks [98] that generate a cipher when energy is available and store this cipher in flash memory for later use. Effectively, this operation translates to the conversion of energy directly into information. This gives rise to a new paradigm of thought of storing of energy in the form of information. If information is equated roughly with energy and vice versa, scenarios can be visualized where energy harvesting networks could reduce the energy consumption of the network as a whole by clever mechanisms such as compressing data by averaging sensor data from several nodes.

- Nodes need to cooperate with peers who have time-varying energy profiles to achieve diversity gain. Nodes share and coordinate their resources to enhance transmission quality even when some nodes are temporarily unavailable. For example, truncated channel inversion concepts, and metrics such as communication outage probabilities based on probabilistic energy injection models have to be considered along with cognitive networking. The goal is to have harvesting nodes cooperating at peer as well as network levels.

## X. CONCLUSION

We have provided a condensation of prominent research on the subject of energy harvesting for sensor networks. The topics surveyed encompass various components, principles and recommendations for the design of energy harvesting nodes and their operation in networks. We also provide some novel observations and recommendations that could improve existing models and designs. This article may help as a guide where most of the current work is being compared. Finally, we provided a list of interesting open problems and challenges for future research in this area.

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