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Energy Harvesting in Wireless Sensor Networks

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Abstract

Wireless Sensor Networks (WSNs) enable many vital applications ranging from environmental monitoring to human health control.

Main research efforts in the WSNs focused on minimizing energy consumption because wireless sensor nodes are mostly powered by batteries which are usually hard to replace.

Recent research on long-lasting WSNs is proposing energy harvesters combined with rechargeable batteries and super capacitors (for energy storage) as the key enabler to "perpetual" WSN operations, in this survey, we address Energy Harvesting Methodologies based on the related literature.

Keywords: *Energy Harvesting, Wireless Sensor Network, Power Consumption, Sources.*

1. Introduction

A collection of sensing nodes which are connected through wireless channels formed a wireless sensor network (WSN) in which the nodes communicate with each other through wireless channels in order to accumulate spatially distributed data about their environment.

WSNs investigation has primarily believed the use of a convenient and inadequate energy source for empowering the sensors, a sensor becomes useless in the absence of energy and becomes unable to contribute to the utility of the network as a group. Therefore, extensive efforts have been used in finding energy-efficient networking protocols for increasing the life span of WSNs.

However, there are promising WSN applications where the sensors are obligatory to work for a long time after their deployments. In these cases, batteries are tough or impractical to replace/recharge. Although, a little amount of power is required for these applications, the useable lifetime of WSNs is decreased by the gradual degradation of the batteries.

With the motivation of raising the usable WSNs around us and to value a number of economic and environmental limitations, researchers are looking for new green and theoretically unlimited energy sources. Harvesting of energy from the ambient energy is the basement of these new sources.

Energy harvesting devices efficiently and effectively capture, accumulate, store, condition, and manage this energy and supply it in a form that can be used to empower WSNs. This harvested energy can be an alternative energy source for adding-on a principal power source and thus increase the consistency of the whole WSN by preventing the disruption of power [4].

Energy Harvesting-based WSNs (EHWSNs) are the result of endowing WSN nodes with the capability of extracting energy from the surrounding environment.

Energy harvesting can exploit different sources of energy, such as solar power, wind, mechanical vibrations, temperature variations, magnetic fields, etc. Continuously providing energy, and storing it for future use, energy harvesting subsystems enable WSN nodes to last potentially forever [1].

The system architecture of an energy harvesting wireless sensor node includes the following components:-

1) The energy harvester(s).

2) Power management module, that collects electrical energy from the harvester and either stores it or delivers it to the other system components for immediate usage.

3) Energy storage, for conserving the harvested energy for future usage.

4) Microcontroller.

5) Radio transceiver.

6) Sensory equipment.

7) Analog to Digital Converter.

8) Storage Memory.

The reminder of this paper is organized as follows: section 2 shows general architecture of the energy subsystem of an EHWSN, section 3.

Shows scopes of energy harvesting for wireless sensor network section 4 Shows the different sources from which energy can be harvested.

2. Architecture of the energy subsystem of an EHWSN

The general architecture of the energy subsystem of an EHWSN node is shown in Figure 1.

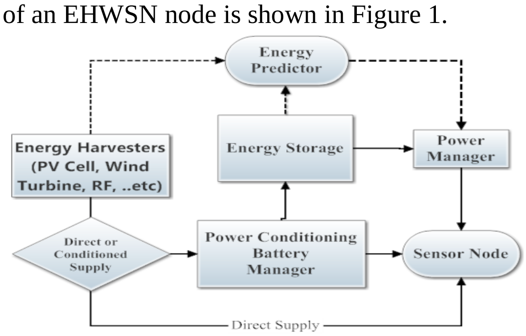

Fig. 1 Architecture of the energy subsystem of an EHWSN node [1]

Although in some application it is possible to directly power the sensor node using the harvested energy, with no energy storage (also known as harvest-use architecture), in general this is not a viable solution.

When the harvesting rate is greater than the current usage the buffer component can store excess energy for later use, thus supporting variations in the power level emitted by the environmental source [1].

The two alternatives commonly used for energy storage are secondary rechargeable batteries and supercapacitors (also known as ultracapacitors), Supercapacitors are similar to regular capacitors, but they offer very high capacitance in a small size.
Supercapacitors offer several advantages with respect to rechargeable batteries:-

1) Can be recharged and discharged virtually an unlimited number of times, while typical life-times of an electrochemical battery is less than 1000 cycles.
2) Can be charged quickly using simple charging circuits, thus reducing system complexity.
3) Do not need full-charge or deep-discharge protection circuits.
4) Have higher charging and discharging efficiency than electrochemical batteries, the charge cycle of a super capacitor can be more than half a million with a 10 year functioning lifetime before the energy capacity is reduced to 80% [4].
5) More environmental friendly than disposable batteries.
6) Energy is deposited at higher energy density and its small form factor is suitable for WSNs [4].

Both types of storage devices deviate from ideal energy buffers because they have limited size and storage capacity and charging and discharging efficiency less than one.

3. Tables, Scopes of Energy Harvesting for Wireless Sensor Network

3.1 Power Management

For maximizing the benefits of harvested energy, efficient power management is important.

Harvesting aware power management (HAPM) strategies have been presented for energy harvesting systems that retain devices operated in an energy neutral mode. The authors have studied the advantages and disadvantages for three unlike approaches of HAPM, which are duty cycling, frequency scaling and maximum power point tracking [4].

The conclusion is that the best choice is the dynamic or adaptive power management for energy harvesting systems.

A significance of using energy harvesting devices in WSN is that traditional metrics cannot be used for power management, in its place, imminent energy availability statistics are required for making decisions about optimal routing [5].

To accomplish this, an environmental energy harvesting framework [6] has been suggested to acquire information about energy environment.

Using this information, the performance of WSN can be improved by efficiently exploiting the energy resources. A power management system along with an analytical model has also been developed [7] for the prediction of various performance metrics, adaptive duty cycles and other correlated features.

A more reasonable approach is to add a power management system between the harvesting source and the load, which attempts to satisfy the energy consumption profile from the available generation profile.

Another method is proposed by assuming two transmission modes of sensors [8]. Therefore, researchers have great chances to improve the power management for efficient WSN use.

3.2 Data Delivery Scheme

Energy conservation remains as the main objective of the WSN networking protocol scheme.

A polling-based medium access control (MAC) protocol has been proposed for the use of sensors powered by ambient vibrations, but optimization has not done, Cooperative transmission protocols for wireless communications have also been suggested for energy harvesting in wireless sensor nodes [4].

Directed Diffusion is one of the initial WSN routing protocols, which has been revised to integrate data about the supply of power (solar or battery power) of nodes, the results show that the performance of solar-aware variant is better than the shortest path routing.

However, the environment can provide a limited amount of power and therefore, a routing algorithm has to be established, which considers the actual environmental conditions, the key idea is to model the flow network and attain appropriate explanation by resolving the max flow problem for maximizing throughput. The alternative solution integrates the energy replacement ratio hooked on the cost metric during routes computing [4].

3.3 Topology and Connectivity

Power control is one of the important issues for maintaining connectivity over topology control. If the harvested energy is not sufficient for supplying continuous power to the sensor node, the nodes have to go to sleep for battery charging.

This modifies the network topology and connectivity. Different sleep and wakeup performance strategies are based on different factors, for instance channel state, battery state and environmental conditions and these are analyzed in [9].

Game theory can also be applied for finding the optimal parameters for the scheme of sleep and wakeup to compromise between packet blocking and dropping probabilities another analytical framework has also been presented in [10] for the estimation of various statistical properties of the system, It has also been presented that sensor networks clustering can be upgraded by considering energy harvesting process's characteristics.

4. Methods of Energy Harvesting

A number of authors have proposed different suitable energy sources for harvesting, in [11], energy sources are clustered as human and environmental with sub-classes of kinetic and thermal.

Buren [12] has presented an analogous grouping of energy sources as thermal energy, radiant energy, and mechanical energy sources.

4.1 Mechanical Energy Harvesting

The process of converting mechanical energy into electricity by using vibrations, mechanical stress and pressure, strain from the surface of the sensor, high-pressure motors, waste rotational movements, fluid, and force. The principle behind mechanical energy harvesting is to

convert the energy of the displacements and oscillations of a spring-mounted mass component inside the harvester into electrical energy.
Mechanical energy harvesting can be: Piezoelectric, electrostatic and electromagnetic.

4.1.1 Piezoelectric Energy Harvesting

When a force or stress is applied to a piezoelectric material, it leads to an electric charge being induced across the material. This is known as the direct piezoelectric effect.

In piezoelectric energy harvesting from vibration, a mass is suspended by a beam, with a piezoelectric layer on top of the beam, when the mass vibrates, the piezoelectric lever is mechanically deformed and a voltage is generated. The most common energy harvesting systems are cantilever structures that are mainly designed to operate at their resonance frequencies [2].

Such structures are popular because they enable relatively high stress levels on the piezoelectric material while minimizing the dimensions of the devices, Figure (2) shows such a system composed of a piezoelectric patch which is bonded to the host cantilever beam surface, which is under alternating deformation.

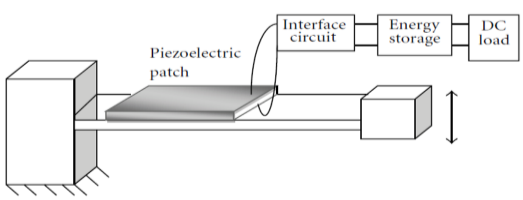

Fig. 2 Architecture of the energy subsystem of an EHWSN node [1]

When the beam is excited by mechanical vibration in the host structure, a large strain is induced in the piezoelectric material and an alternating voltage (AC) is generated between the electrodes.

The AC voltage is then conditioned by interface circuits for proper delivery of the harvested energy to a storage element or compatibility with load specifications.

A simple nanogenerator is principally a nanowire which is a one-dimensional nanomaterial that has a typical diameter less than 100nm and a length of 1μm , the majority of ceramic nanowires are in fact single crystal materials[2].

Compared to the conventional ceramic/thin film-based piezoelectric cantilever energy harvesting devices, nanogenerators offer three distinct advantages:-

1) Enhanced Piezoelectric Effect. When a strain gradient is experienced by a ferroelectric nanowire, 400–500% enhancement of the piezoelectric effect can be achieved.

2) Superior Mechanical Properties. The lattice perfection of nanowires enables much larger critical strain, higher flexibility, and longer operational lifetime compared to conventional ceramic microgenerators.

3) High Sensitivity to Small Forces. Large aspect ratio and small thickness allow the creation of significant strain in the nanowires under a force at the nanonewton or piconewton level.

There is still a need to improve the power output of piezoelectric generators to match the requirements of wireless sensor devices, this challenge can be addressed by using piezoelectric material with the best piezoelectric properties, the best device geometries, and the best power electronics to condition and manage the power output [2].

Energy harvesting using piezoelectric generators is an attractive alternative energy source that has the potential to provide energy autonomy to wireless sensor devices.

4.1.2 Electrostatic Energy Harvesting

Electrostatic harvesters harness the work ambient vibrations exert on the electrostatic force of a variable capacitor (i.e., varactor). In more physical terms, vibrations cause the gap distance and/or overlap area of a parallel-plate capacitor (C_{VAR}) to vary with a net effect, under constant charge or voltage conditions, of producing electrical energy [3].

When constraining charge by keeping the capacitor open circuited, voltage increases with decreasing capacitance, according to Eq. (1), thus increasing the potential energy stored in the capacitor since the increasing squared effects of voltage on energy offset the decreasing linear effects of capacitance according to Eq. (2).

$$Q_{CONSTANT} = C_{VAR}V \quad (1)$$

$$E_{CAP} = ½CV^2 \quad (2)$$

Similarly, by constraining voltage, the mechanical energy moving the capacitor plates drives charge out of the capacitor, according to Eq.(3) yielding a net harvesting current i_{HARV} which can be calculated using Eq. (4)

The maximum voltages charge-constrained systems produce, however, surpass the breakdown limits of most modern CMOS technologies by a considerable margin. A 200 pF variation, for instance, amplifies the initial voltage across CVAR by a factor of 200, by its maximum-minimum capacitance ratio producing peak voltages of roughly 25-200 V from inputs as low as 125 mV to 1 V [3].

In the proposed system in [3], the voltage across the capacitor is held constant by the already-existing energy-storage device (i.e., the rechargeable battery), the one ultimately receiving the harvested energy.

In this way, the harvester avoids the use of additional voltage sources, electrostatic means are probably most compatible with CMOS integration because the harvesting device is a relatively simple variable plate distance capacitor built with standard micro-electromechanical systems (MEMS) technologies [3].

4.1.3 Electromagnetic Energy Harvesting

There are some regions of the electromagnetic spectrum of very high ambient energy levels and also some other regions of lower ambient energy levels. The conversion efficiency of electrical energy is also dependent on the portion of the considered spectrum.

Analysis of electromagnetic waves shows that the power density produced by an antenna is approximately equal to E^2/Z_0, where Z_0 is the radiation resistance of free space (377 Ω) and E is the local electric field strength in volts/meter, thus, a 1 V/m electric field gives up 0.26 μ W/cm2.

However, this order of electric fields is uncommon except when close to a powerful transmitter, a solution to this problem can be the deliberate transmission of RF energy only for the use of powering devices [4].

This practice is common place in Radio Frequency Identification System (RFID) which derives energy inductively, capacitively or radiatively from the tag reader, some of the currently available products that harvest energy from the electromagnetic fields include the power donut and power line sensor, there are two different principles on which RFID tags are powered - Active and Passive, active RFID tags are powered by batteries. Passive RFIDs derive power autonomously using the RF signals from the base station [4].

4.2 Photovoltaic Energy Harvesting

The process of converting incoming photons from sources such as solar or artificial light into electricity, solar energy harvesting has been prevalent for a long time and has become a mature technology now. Solar energy can be harnessed with the help of a PV system that converts sunlight into electricity [4].

PV cells consist of a P-N junction. Upon exposure to light the cell releases electrons, Photovoltaic energy conversion is a traditional, mature, and commercially established energy-harvesting technology. It provides higher power output levels compared to other energy harvesting techniques and is suitable for larger-scale energy harvesting systems [1].

Solar panels are characterized by two parameters, the open circuit voltage (Voc) and the short circuit current (Isc), a solar panel behaves as a voltage limited current source. As the amount of incident solar radiation decreases (increases), the value of Isc also decreases (increases), however, Voc remains almost constant, due to its current source-like behavior, it is difficult to power the load system directly from the solar panel. Hence, an energy storage element, such as a rechargeable battery or an ultra-capacitor, is used to store the energy harvested by the panel and provide a stable voltage to the system [4].

However, its generated power and the system efficiency strongly depend on the availability of light and on environmental conditions. Other factors, including the materials used for the photovoltaic cell, affect the efficiency and level of power produced by photovoltaic energy harvesters [1].

4.3 Thermal Energy Harvesting

Implemented by thermoelectric energy harvesting and pyroelectric energy harvesting.

1. A thermoelectric harvester scavenges the energy based on the Seebeck effect, which states that electrical voltage is produced when two dissimilar metals joined at two junctions are kept at different temperatures, this is because the metals respond differently to the temperature difference, creating heat flow through the thermoelectric generator.

   This produces a voltage difference that is proportional to the temperature difference between the hot and cold plates. The thermal energy is converted into electrical power when a thermal gradient is created. Energy is harvested as long as the temperature difference is maintained.

2. Pyroelectric energy harvesting is the process of generating voltage by heating or cooling pyroelectric materials. These materials do not need a temperature gradient similar to a thermocouple. Instead, they need time-varying temperature changes.

Changes in temperature modify the locations of the atoms in the crystal structure of the pyroelectric material, which produces voltage. To keep generating power, the whole crystal should be continuously subject to temperature change. Otherwise, the produced pyroelectric voltage gradually disappears due to leakage current.

Pyroelectric energy harvesting achieves greater efficiency compared to thermoelectric harvesting, On the other hand, thermoelectric energy harvesting provides higher harvested energy levels.

Because of the various sizes of thermal harvesters, they can be placed on the human body, on structures and equipment.

4.4 Wireless Energy Harvesting

This includes RF energy harvesting and resonant energy harvesting.

RF energy harvesting is the process of converting electromagnetic waves into electricity by a rectifying antenna, or rectenna. Energy can be harvested from either ambient RF power from sources such as radio and television broadcasting, cellphones, Wi-Fi communications and microwaves, or from EM signals generated at a specific wavelength.

Although there is a large number of potential ambient RF power, the energy of existing EM waves are extremely low because energy rapidly decreases as the signal spreads farther from the source.

Such RF energy harvesting is able to efficiently deliver powers from micro-watts to few milliwatts, depending on the distance between the RF transmitter and the harvester.

Resonant energy harvesting Also called resonant inductive coupling, is the process of transferring and harvesting electrical energy between two coils, which are highly resonant at the same frequency.

Specifically, an external inductive transformer device, coupled to a primary coil, can send power through the air to a device equipped with a secondary coil. The primary coil produces a time-varying magnetic flux that crosses the secondary coil, inducing a voltage.

In general, there are two possible implementations of resonant inductive coupling: Weak inductive coupling and strong inductive coupling [1].

4.5 Wind Energy Harvesting

The process of converting air flow (e.g., wind) energy into electrical energy. A properly sized wind turbine is used to exploit linear motion coming from wind for generating electrical energy. Miniature wind turbines exists that are capable of producing enough energy to power WSN nodes.

However, efficient design of small-scale wind energy harvesting is still an ongoing research, challenged by very low flow rates, fluctuations in wind strength, the unpredictability of flow sources, etc. Furthermore, even though the performance of large-scale wind turbines is highly efficient, small-scale wind turbines show inferior efficiency due to the relatively high viscous drag on the blades at low Reynolds numbers [1].

4.6 Acoustic Energy Harvesting

The process of converting high and continuous acoustic waves from the environment into electrical energy by using an acoustic transducer or resonator. The harvestable acoustic emissions can be in the form of longitudinal, transverse, bending, and hydrostatic waves ranging from very low to high frequencies.

The efficiency of harvested acoustic power is low and such energy can only be harvested in very noisy environments. Harvestable energy from acoustic waves theoretically yields $0.96\mu W/cm^3$, which is much lower than what is achievable by other energy harvesting techniques. As such, limited research has been performed to investigate this type of harvesters.

All previously described harvesting techniques can be combined and concurrently used on a single platform (hybrid energy harvesting).

The power density expresses the harvested energy per unit volume, area, or mass. Common unit measures of power density include watts per square centimeter and watts per cubic centimeter.

Conversion efficiency is defined as the ratio of the harvested electrical power to the harvestable input power. The energy conversion efficiency is a dimensionless number between 0 and 100%.

5. Conclusions

With the advancement on energy harvesting techniques, and the development of small factor harvester for many different energy sources, EHWSNs are poised to become the technology of choice for the host of applications that require network functionalities for years or even decades.

Through the definition of new hardware and communication protocols specially tailored to the fundamentally different models of energy availability, new applications can also be conceived that rely on "perennial" functionalities from networks that are truly self-sustaining and with low environmental impact.

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