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Current Developments of Energy Scavenging, Converting and Storing in WSNs

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ABSTRACT

Wireless sensor networks (WSNs) design requires multi-disciplinary approach in the field of wireless communication, embedded systems, networking, digital signal processing, hardware and software engineering. Major factors to influence the WSNs design are hardware and software constraints, scalability, cost, transmission media, network topology and power consumption etc. Most of WSN nodes are battery powered. With the limited capacity of batteries to power WSN nodes, need of energy harvester or scavenger is required to harvest or scavenge energy from the environment to improve the life-time of the sensor node. The harvested or scavenged energy is converted by power converters to recharge the sensor nodes or for the storage devices. This paper gives current developments of energy harvesting technologies, power converters and storage devices proposed by various researchers in WSNs along with some open research problems.

Keywords

Energy Harvesting, Power Management System, Wireless Sensor Networks, Power Convertors, Energy Storage Devices.

1. INTRODUCTION

Scavenging energy from the environment is an enviable and growingly important means in several emerging applications of embedded systems such as wireless sensor networks. The process by which energy is derived from surrounding sources like vibration energy, light energy, thermal energy, wireless energy, wind energy, chemical energy, acoustic energy, etc. is captured and stored in order to power such systems like wireless sensor networks is termed as Energy harvesting or scavenging [1].

Sensor nodes are commonly power driven by battery, but when the number of nodes and size is augmented the replacement of washed-out batteries is quite complicated and profligate. In many researches upper energy-density batteries and supercapacitors are exploited, but the accessible energy amount is still cruelly limits the system’s natural life. Consequently, there is an obvious impose to explore novel alternatives to power driven sensor nodes. As a result Sensor networks can accomplish much larger run-times, years not months, with potentially lesser cost and weight by harvesting energy from their local environment [2].

For power driven wireless sensor nodes there are three main technology categories: energy harvesting or scavenging, energy converting and energy storage. This paper reviews the state-of-the art technology in all of these fields. These include energy scavenging sources like vibration energy, light energy, thermal energy, wireless energy, wind energy, chemical energy, acoustic energy etc., energy converters such as DC-DC converters, DC-AC converters, AC-DC rectifiers and energy storage utilizing batteries and supercapacitor.

According to the magnitude of output power and impedance, the harvested energy can be used directly or stored into energy storage device There are numerous technologies rising on the market that aspire at converting these ambient energy sources into useable electrical energy. One can exploit the existing energy in the environment to produce electricity at any given locality to deliver power for wireless sensor nodes.

There is necessity to merge the design and fabrication with appropriate interface circuit for the objective of realizing self-power of wireless sensor nodes. Each has its own unique output characteristics (open circuit voltage, short circuit current and maximum power operating point) [3]. It would be desirable to develop a universal means of converting the electrical energy derived from energy harvesters, that are both apt in size and cost, and storing it in a form that is suitable for powering electronic devices.

This paper is a review of various energy scavenging sources, power converters and energy storage systems. Collectively, this type of device could be used in concurrence with energy harvesting technologies to provide an attractive solution to the problem of powering wireless sensor network nodes.

2. ENERGY SCAVENGING TECHNIQUES

Figure 1 shows the present energy harvesting techniques used in different WSN applications. This mainly comprises of Vibration, Light, Thermo, Wireless, Wind, Biochemical, and Acoustic energy sources. The comparison of various energy harvesting techniques in terms of power density is given in Table 1. Current developments in energy harvesting are discussed below in this section.

2.1 Vibrtion

Vibration energy can be harvested from different means and by converting this energy into electricity. Vibration energy harvesting is separated in three categories: Electromagnetic, Electrostatics and Piezoelectric [4].

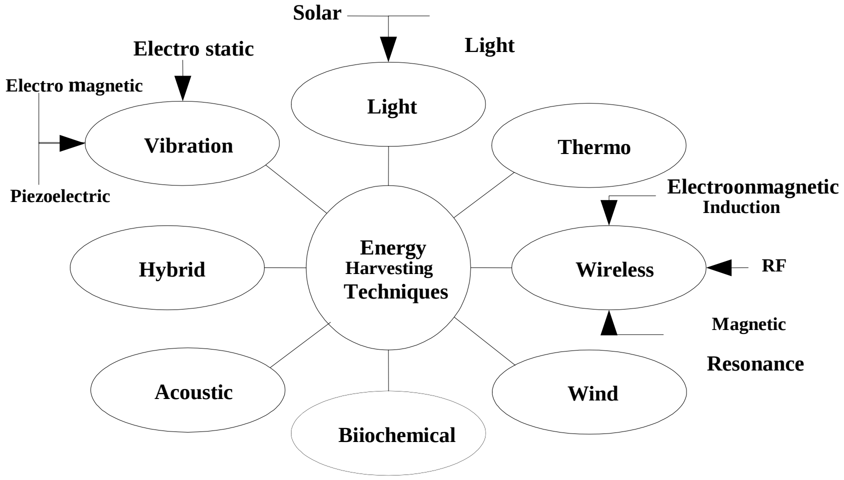

Fig 1: Energy Harvesting Techniques used in WSN applications.

Table 1. Comparison of various energy harvesting Techniques

Energy Harvesting Techniques for WSN		Power Density
Vibration	Pizoelectric	330 µW/ Cm^3
	Electrostatic	50-100 µW/ Cm^3
	Electromagnetic	184-306µW/ Cm^3
Solar(Photovoltaic)	Indoor	10-100µW/ Cm^2
	Outdoor (bright day)	15mW/ Cm^3
Thermal	Thermoelectric	40 µW/ Cm^3
	Pyroelectric(at 8.5ºC/s)	8.64 µW/ Cm^2
Wireless	RF Energy	0.01-0.1 µW/ Cm^2
Wind	At 5m/s	16.2 µW/ Cm^2
Acoustic	At 100 db	0.96 µW/ Cm^3
	At 75 db	3nW/ Cm^3

2.1.1 Electromagnetic

Electromagnetic transduction is based on the generation of voltage resulting from a relative motion between a coil and a magnet [5]. The electromagnetic vibration energy harvesters can be simply packaged to reduce the risk of corrosion and eliminate the temperature limit. Many researchers focus on electromagnetic vibration energy harvesters ranging from micro electro mechanical (MEM) devices to larger scale devices with the dimensions of order of a few centimeters. It has been shown that an optimized device is capable of converting up to 30% of the total energy supplied into useful electrical energy [6]. There are four available magnets: ceramic, Alnico, SmCo, and NdFeB, among these, NdFeB has the largest magnetic field intensity, high coercive force, and no demagnetization due to the vibration of generator [7].

Rahimi et al. proposed a vibration-based electromagnetic energy harvester system powering a 1.5V, 15 μA loads with 65% conversion efficiency, and 5% ripple at an external vibration frequency of 10Hz and the maximum output power of 22.5 μW [8].

Tao et al. proposed a micro electromagnetic vibration energy harvester with dimension of 4.5 × 4.5 × 1mm^3 and total volume of 20mm^3 [9]. This study offers a solution of the micro electromagnetic harvester fully integrated with MEMS fabrication technology, although the produced energy is very limited.

2.1.2. Electrostatic

The principle of electrostatic energy harvesting is based on the stucture of variable capacitor to produce charges from a relative motion between two plates [10]. For a parallel plate capacitor with plate area *A* and plate separation *D*, the capacitance is approximately given by the following equation.

$$C = \frac{\varepsilon A}{D} = Q/V \qquad (1)$$

Where ε is the dielectric constant of the insulating material between the plates, *Q* and *V* are the charge and the voltage on the capacitor, respectively [11,12,13]. The energy stored on the capacitor is

$$\mathrm{E} = 1/2\mathrm{QV} \qquad (2)$$

If the charge is constant, then combining (1) and (2), the energy becomes

$$\mathrm{E} = \mathrm{Q}^2\mathrm{d}/2\varepsilon\mathrm{A} \qquad (3)$$

While if the voltage is constrained, the energy becomes [14]

$$\mathrm{E} = \varepsilon\mathrm{A}\mathrm{V}^2/2\mathrm{d} \qquad (4)$$

Sidek et al. designed and simulated an SOI-MEMS electrostatic vibration energy harvester of the size of micron level using the architect module with CoventorWare 2010 [15]. Simulation results show that the harvester is capable of generating power of 5.891 μW at the resonant frequency of 2 kHz that is too high compared to the frequency of ambient vibration.

Sheu et al. developed an in-plane, gap overlap combdrive electrostatic vibration energy harvester with a mass of 4.9mg to deliver an average output power of 0.0924 μW when harvesting 10 μm amplitude of motion at 105Hz and the size of the harvester was 3000 μm × 3000 μm × 500 μm [16]. The harvester is implemented by CMOS process on chip. The harvester is of small size, and the energy harvested is also at a very low level, targeted only at very low power applications.

2.1.3. Piezoelectric

When the Piezoelectric materials are under stress or strain they generate charge. They generally consist of piezoelectric monocrystal, piezoelectric ceramics, piezoelectric polymers, and piezoelectric composites. Piezoelectric ceramic PZT is the most frequently used in present days. Piezoceramics have the mature manufacturing process, cheaper, large electromechanical coupling constants, and high energy conversion rate. As per the different structures, piezoelectric transducers can be separated into unimorph, bimorph, rainbow type, cymbal type, moonie type, stack type, and so forth [17].

Sarker et al. presents a design of battery-less piezoelectric based energy harvesting interface circuits with 300mV step-up voltage in which DC-DC Step-Up converter technique was used for designing the startup voltage with low voltage energy [18]. They have achieved a boost up of minimum 1.67 V in there developed circuit for input DC voltage of 300mV.

Sankman et al. presented an industrial application where vibrations at 60 Hz are commonly found, for example from motors, air ducts and have a high power density of up to 375 $\mu W/cm^3$[19].

The three methods of harvesting vibration energy have different advantages and disadvantages in the field of power density, integration with MEMS and IC technology, electrical matching, and so on. But the efficiency of those is related to the vibration frequency due to the mathematical fact that the maximum power output from vibration-based generators is proportional to the cube of the vibration frequency and drops dramatically at low frequencies (1–100Hz) [20]. Because the main frequencies in the environment are relatively low, the mechanical energy harvester may need to utilize the upconverter to transform the low frequency into high frequency so as to achieve an increased power output. Among the three vibration energy harvesting methods, the piezoelectric and electrostatic harvesters have the ability to generate voltage ranging from 2 to 10V and implemented for small scale energy harvestors, but the electromagnetic harvesters can produce a maximum voltage of 0.1V only and implemented for larger devices [21].

2.2 Light

Light energy can be harvested from solar and artifiacial light from the ambience. Solar power can be extract as solar thermal power and solar photovoltaic. One is for large scale and another is for WSNs or small/nano scale. Solar photovoltaic is discussed in this paper. According to the photovoltaic principle, solar cells are used to convert sunlight into electrical power directly [22,23]. Other lights such as fluorescent and infrared can also be used as the power source for solar cells. According to the materials used, solar cells can be divided into four categories: (i) silicon solar batteries (ii) multicompound solar cells (iii) polymer solar batteries (PPVC) (iv) nanocrystalline solar cells. The silicon solar batteries are most commonly used in today’s technology. At present, polycrystalline silicon solar cells for conditions of high-intensity light and outdoor spectrum acquire the largest production and market share, followed by monocrystalline silicon solar cells [24,25].

Brunelli et al. presented a batteryless solar-harvesting circuit which performs maximum-power-point tracking of solar energy collection under nonstationary light conditions, with high efficiency and low energy cost exploiting miniaturized PV modules [26]. The scavenger improves the power consumption of less than 1 mW. Efficiency up to 80% and ideality diverging by less than 10% is obtained.

Dondi et al. presented a solar energy harvesting circuit for low-power applications [27]. Under different light intensities and different switching frequencies the performance of two implemented prototypes intended to power a wireless embedded system is evaluated. Measurements showed those higher switching frequencies allow reaching the maximum efficiency of 90% at higher light intensities, whereas lower operating frequencies perform better under lower irradiance.

Dondi et al. proposed a methodology for optimizing a solar harvester with maximum power point tracking for self-powered wireless sensor network nodes [28]. The focus was on maximizing the harvester’s efficiency in transferring energy from the solar panel to the energy storing device. An analytical model of photovoltaic panel, based on a simplified parameter extraction procedure, was adopted. With discrete components the design procedure helped to reach a maximum efficiency of 85%.

Recently, the scientists are doing work on solar cell which is thinner than spider web. The thickness of this ultrathin solar cell is only 1.9 microns which is equivalent to one tenth of the current thinnest solar battery which is composed of electrodes which are embedded in the plastic tab [29]. The application of this ultrathin, superlight, ultra flexible solar cell in the future includes, portable electronic charging device or for manufacture of electronic textiles. Currently the researchers are increasing the photoelectric conversion efficiency of it. This new solar cell will be place into use within five years.

Also, a new kind of efficient full spectrum solar cell with tandem-type connection based on colloidal quantum dots (CQD) is developed. Its theoretical conversion efficiency is as high as 42%.

2.3 Thermo

Thermal energy harvesting can be divided in thermoelectric energy harvesting and pyroelectric energy harvesting.

2.3.1. Thermoelectric energy

Thermoelectric energy generators (TEGs) are based on Seebeck effect. TEGs convert temperature differences across dissimilar materials into voltage [30].

J Su at el. proposed a micromachined thermoelectric energy harvester with 6 µm high polycrystalline silicon germanium (poly-SiGe) thermocouples fabricated on a 6 inch wafer [31].

Yang at el. proposed a micro-thermoelectric generator (µTEG) design based on stacked polysilicon thermocouples, in which the p- and n-thermolegs of a thermocouple are stacked and insulated [32]. To analyze the optimal thermocouple size by matching their thermal resistance and electrical resistance a thermal model is applied. Analysis showed that the maximum power factor and voltage factor of an optimal thermocouple 100 µm × 4 µm × 0.275/0.18 µm (length × width × thickness for p-/n-thermolegs) is 0.0473 $\mu W/cm^2 K^2$ and 3.952 $V/cm^2 K$, respectively. The voltage factor is about 142% of that in co-planar design. Multiple thermocouples can thus be stacked for higher performance.

2.3.2. Pyroelectric energy

Pyroelectric energy harvesting is about pyroelectric effect, the spontaneous polarization due to temerature changes in certain anisotropic solids [33,34]. A time varing temperature profile is needed for pyroelectric energy harvesting.

Ravindran et al. concluded that pyroelectric generators (PEGs) present a potential alternative to thermoelectric generators (TEGs), to generate electric power from thermal fields. Pyroelectric generators have a predicted upper limit of 50 % of the Carnot's efficiency, which exceeds that of TEGs [35]. The measured power output of such a harvester is 3 µW for a temperature difference of 79.5 K. By improving the harvester design, a power output of approximately 9 mW is predicted.

Nguyen et al. was concerned with designing, building, and testing a pyroelectric energy converter to directly convert waste heat into electricity [36]. A maximum energy density of 130 J/l was achieved at 0.061 Hz frequency with temperature oscillating between 69.3 and 87.6 °C. Furthermore, a maximum power density of 10.7 W/l was obtained at 0.12 Hz between 70.5 and 85.3 °C. In both cases, the low and high electric fields in the Olsen cycle were 202 and 739 kV/cm.

Pyroelectric energy harvesting produces greater efficiency compared to thermoelectric harvesting. Conversely, thermoelectric energy harvesting provides higher harvested energy levels. Due to various sizes of thermal harvesters, they can be placed on the human body, on structures and equipment [37].

2.4 Wireless

Wireless energy harvesting techniques are of two types: RF (Radio Frequency) energy harvesting and resonant energy harvesting.

2.4.1 RF energy

RF energy is harvested from the RF emitted by sources such as radio and TV signals, cell phones, WiFi communications and microwaves [38,39,40]. An energy harvesting system consists of two main subsystems, one is the receiving antenna, which functions to capture ambient RF energy to power up the integrated embedded system and second subsystem is the rectification circuitry, which converts the input RF power into DC output power efficiently [41].

Sim et al. presented two compact patch antenna designs for a new application outdoor RF energy harvesting in powering a wireless soil sensor network [42]. Zakaria et al. presents an overview and the progress achieved in RF energy harvesting, which involves the integration of antenna with rectifying circuit [43]. Different combinations of antenna and rectifier topologies yield diverse results. They expected to give an indication on the appropriate techniques to develop an efficient RF energy harvesting system. Jabbar at el. presents a modified form of existing CMOS based voltage doubler circuit is presented to achieve 160% increase in output power over traditional circuits at 0 dBm input power. A schottky diode based RF energy harvesting circuit performance is also studied with practical and simulations results [44].

2.4.2 Resonant energy

Resonant energy harvesting is also known as resonant inductive coupling. Tuned circuits are used one at receiver and one at transmitter, due to inductive coupling power is transferred by magnetic fields developed between the circuits [45]. Two types of resonant inductive coupling are: Weak inductive coupling and strong inductive coupling [46,47].

2.5 Wind

Wind energy harvesting uses wind turbine generators to convert mechanical energy into electrical energy [48].

Tan et al. presents an optimized wind energy harvesting (WEH) system that uses a specially designed ultra-low-power-management circuit for sustaining the operation of a wireless sensor node [49]. The proposed power management circuit has two distinct features: 1) an active rectifier using MOSFETs for rectifying the low amplitude ac voltage generated by the wind turbine generator under low wind speed condition efficiently and 2) a dc-dc boost converter with resistor emulation algorithm to perform maximum power point tracking (MPPT) under varying wind-speed conditions. An average electrical power of 7.86 mW is harvested by the optimized WEH system at an average wind speed of 3.62 m/s, which is almost four times higher than the conventional energy harvesting method without using the MPPT.

Tan et al. also proposed a satellite-based remote sensing technique which has been widely used in monitoring wildfire spread [50]. An indirect approach in sensing wind speed has been proposed by them as an alternative to the bulky conventional wind anemometer to save cost and space. The experimental results show that the designed WEH system is able to harvest an average electrical power of 7.7 mW at an average wind speed of 3.62 m/s for powering the operation of the wireless sensor node that consumes 3.5 mW for predicting the wildfire spread.

Cammarano et al. present a novel energy prediction model, named Pro-Energy (PROfile energy prediction model), for multi-source energy harvesting WSNs, which is able to leverage past energy observations to provide accurate estimations of future energy availability [51].

2.6 Biochemical

Biochemical energy harvesting involves biological entity. Biological energy is generated due to motion, stretch or matabolic processes in the biological entity that can be converted into electrical energy. Human body includes many bilogical entities. Even though biochemical energy harvesting can be superior to other energy harvesting techniques in terms of continuous power output and biocompatibility, its performance depends on the type and availability of fuel cells [52].

Hansen et al. presented a hybrid energy scavenging device for potential in vivo applications [53]. The hybrid device consists of a piezoelectric poly(vinylidene fluoride) nanofiber nanogenerator for harvesting mechanical energy, such as from breathing or from the beat of a heart, and a flexible enzymatic biofuel cell for harvesting the biochemical (glucose/O_2) energy in biofluid, which are two types of energy. The two energy harvesting approaches can work simultaneously or individually, thereby boosting output and lifetime.

2.7 Acoustic

Acoustic energy harvesting performs conversion of acoustic energy into electrical energy by using piezoelectric transduction [54]. Piezoelectric and electromagnetic based acoustic energy harvesters are developed [55].

3. CONVERTORS

There are a number of different circuit topologies that allow the conversion of electrical energy.

- DC–DC converters- Step up(Buck), Step Down (Boost), Step-up/step-down(buck-boost), Full bridge Converters
- DC-AC inverters

- AC-DC rectifiers- both controlled DC output and uncontrolled DC Output

Dahiya et al. presented the design of wireless sensor network (WSN) in energy conversion module based on multiplier circuit. This energy conversion module can function as an AC to DC converter that not only rectifies the input AC signal but also elevates the DC voltage level [56]. Two types of multiplier circuits namely single stage multiplier circuits and multistage multiplier circuits to design the wireless sensor networks are used. Mathematical analysis also presented for the single and multistage multiplier circuits. Efficiency and multistage voltage output are the two parameters use to analysis the performance of the designed WSN based on multiplier circuits. Simulation results show the relationship between output voltage and RF power of the WSN system with different level of multipliers stage. Results shows that the efficiency analysis of the WSN with the different multiplier stages. Graphical results show that the efficiency of the system goes on increases with the increase in the multipliers stages. Results show the effectiveness of the designed system.

Rao et al. presents an efficient ac-to-dc power converter that avoids the bridge rectification and directly converts the low ac input voltage to the required high dc output voltage at a higher efficiency [57]. The proposed converter consists of a boost converter in parallel with a buck–boost converter, which are operated in the positive half cycle and negative half cycle, respectively. Detailed analysis of the converter is carried out to obtain relations between the power, circuit parameters, and duty cycle of the converter.

Anyway, the universal means of converting energy from sources with differing output characteristics is an open research problem with different storage devices.

4. STORAGE

The energy storage devices considered include rechargeable batteries and supercapacitors. Supercapacitor and rechargeable batteries are common choice of energy storage, are made up of several chemical compositions. Some common rechargeable storage technologies are Nickel Metal Hydride (NiMH), Nickel Cadmium (NiCd), Lithium Ion (Li-ion) and Sealed Lead Acid (SLA). These technologies can be characterized along several axes energy density, power, storage efficiency, discharge rate and number of deep recharge cycles [58]. Table 2 shows the typical values of output voltage, energy density and recharge cycles across different storage technologies.

Table 2. Comparison of storage Technology

Storage Technology	Output Voltage(volt)	Energy Density(MJ/kg)	Recharge Cycles
NiMH	1.2	0.11-0.29	1000
NI-cadmium	1.2	0.14-0.22	1500
Li-ion	3.6	0.58	1200
Sealed Lead acid	.6	0.11-0.14	500-800
Super Capacitor	>4	5-8	>1 million

Table 2 shows that lithium ion batteries have higher output voltage, energy density and recharge cycle among all batteries. But the supercapacitor has the highest output paramerers. Though NiMH has better energy density than NiCd, but NiCd has high number of deep recharge cycles. Sealed Lead Acid has the lowest values for energy density and number of cycles and hence is the least effective storage technology. From the perspective of using batteries for storing harvested energy, the supercapacitor storage technology appears to be the best. Advantage of supercapacitor is that it does not suffer from memory effect—loss of energy capacity due to repeated shallow recharge. Another popular battery technology is Nickel-Metal Hydride. NiMH batteries have reasonably high energy and recharge cycles. An advantage of NiMH batteries is that they can be trickle charged, i.e., directly connected to an energy source for charging. Though NiMH batteries suffer from memory effect, the effect is reversible by conditioning fully discharging the battery after charging it. Alternatively, super-capacitors can be used instead of or along with rechargeable batteries as storage components. Like batteries, super-capacitors also store charge, but they self-discharge at a higher rate than batteries. Theoretically, super-capacitors have infinite recharge cycles, and therefore have no limit to the number of times they can undergo deep recharge.

Guan et al. compares several energy storage devices including conventional capacitors, rechargeable batteries, and supercapacitors in piezoelectric energy harvesting [59]. Their charge/discharge efficiency, adaptability, lifetime, and self-discharge are investigated and discussed. A quick test method is proposed to experimentally study the charge/discharge efficiency of the energy storage devices. The results show that the supercapacitors are suitable and more attractive than the rechargeable batteries as energy storage devices in energy harvesting for wireless sensor networks.

5. CONCLUSION

Energy harvesting or scavenging from the ambience is one of the better options to improve the life-time of wireless sensor networks by replacing batteries. In many cases, the harvested or scavenged energy is not enough to power the sensor nodes. Power converters are used to convert the available power to recharge the batteries or to be stored in storage devices. Due to these limitations of low harvested energy from the environment, researches are working to develop a novel power converter and energy storage system used along with energy harvestor or scavenger system to provide an appropriate solution to the problem of powering nodes in wireless sensor networks for different application scenarios. Many energy sources have no commercial solution in the market and needs extensive research. Anyway energy harvester, power converters and storage devices collectively remain an interesting research topic to provide one of the best solutions to power sensor nodes in the field of wireless sensor networks.

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