Energy Harvesting Technologies - Potential application to Wearable Health-Monitoring

Faisal Ahmed[1], Yannick Le Moullec[1], Paul Annus[1]
[1]*T.J. Seebeck Department of Electronic, Tallinn University of Technology,*
Ehitajate tee 5, 19086 Tallinn, Estonia.
faisal@elin.ttu.ee

***Abstract*— WSN are increasingly used for numerous purposes from last few decades; however, the autonomy of nodes in WSNs is still a major challenge. Recent research has resulted in various ideas for extending the nodes operating life-time in accordance to their power and/or usage so as to overcome the challenges and inconvenience related to e.g. battery replacement in an already deployed system. This paper provides a concise review of energy harvesting methods/technologies that can increase the autonomy of wireless sensor network (WSN) nodes. It then presents a wearable health-monitoring application and discusses the suitability of various energy harvesting technologies with respect to typical human activities and behaviours.**

***Index Terms*— Energy Harvesting, Wireless Sensor Nodes, Photovoltaic cell.**

I. Introduction

The concept of energy extraction from nature, which can be used to recharge or replace the conventional power sources, is called energy harvesting. Thus, energy harvesting is deemed to be a very promising approach for enhancing the life-time of sensor nodes. Energy harvesting is one of the best proposed ideas for recharging or even replacing the power source of WSN nodes, which logically results in increased autonomy. Energy harvesting is also known by other terms such as power harvesting, energy scavenging, and free energy (energy derived from renewable energy). [1]

WSN nodes typically contain various components such as a power source, a microprocessor, an external memory, one or several sensors, A-to-D converters and an RF transceiver. In WSNs, such nodes are linked together by means of a wireless communication system to serve various applications such as; observing the environment, detecting/tracking the movement of objects, monitoring human and structure health, etc. The signals collected by the sensors are typically scaled/magnified into the shape of electrical signals for longer periods of times (possibly ranging from days to years). Generally, WSNs use conventional power or fixed power source (e.g. batteries), which are difficult to replace in case of battery drainage or when they becomes weaker, especially if WSNs are deployed in large numbers and are located around unapproachable environments such as deserts, glaciers, jungles and oceans etc.

Sensor nodes can use rechargeable or non-rechargeable batteries. Typically, a non-rechargeable battery is alkaline- based and handy for micro-sensors with low power consumption, e.g. 50μW, whereas a rechargeable battery is based on lithium-ion and is widely used in sensor nodes that makes used of energy harvesting technologies [5].

Thus, energy harvesting can be a valuable asset in various applications such as wearable health-monitoring, which is really challenging due to some factors like convenience, trust, cost, portability, and reliability. Thus, for such applications, harvesting energy is highly desirable and could possibly exploit e.g. human movements (kinetic energy harvesting), body temperature (Seebeck and Peltier effects) as well as ambient energy such as solar and RF waves.

Table 1 shows various sources and corresponding amounts of power that can be used for energy harvesting purpose [2]-[3]-[4].

TABLE I. ENERGY HARVESTING SOURCES AND CORRESPONDING PERFORMANCE [3]-[4].

Energy Source	Conditions	Performance
Solar	Outdoors	7500 $\mu W/\ cm^2$
Solar	Indoors	100 $\mu W/cm^2$
Vibration	1$m/\ s^2$	100 $\mu W/\ cm^2$
RF	Wi-Fi	0.001 $\mu W/\ cm^2$
RF	GSM	0.1 $\mu W/\ cm^2$
Thermal	ΔT = 5 ºC	60 $\mu W/\ cm^2$

II. Energy harvesting technologies

Generically, a sensor which uses energy harvesting techniques consists of an energy harvester module, an energy storage unit such as a super capacitor, a microcontroller and a transmitter [10], as shown in Fig.1.

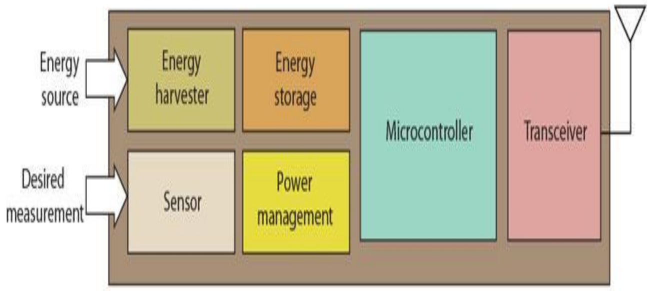

Fig. 1. Generic block diagram of a wireless sensor network node with energy harvesting, energy storage, and power management capabilities [9].

Some of the most common energy sources that can be used as an energy harvesting technologies in WSNs are discussed in what follows.

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A. *Solar Energy*

Solar energy is one of the most powerful and best solutions as an energy harvesting source for wireless sensor networks, especially in outdoor conditions (see Table I). Solar electric systems are made up of photovoltaic (PV) semi-conductors which can be coupled with wireless sensor nodes for extracting energy. Idealistically, PV works in a reasonably sunny climate. PV converts the visible light into direct current (DC), which eliminates the requirement of any further circuit for current conversion [6]. Solar cells are typically constructed from crystalline silicon (c-Si). Various forms of silicon such as mono-crystal, multi-crystal, micro-crystal and amorphous are used in the making of Photovoltaic cells [7]. Solar has the long list of applications; in fact there is hardly any home or office that does not have at least one solar-power calculator. It has a small panel photovoltaic (PV) cell to top it up. Solar cells are used in consumer and industrial applications, including street lighting controls, portable power supplies and satellites [16].

However, solar electric systems have a major limitation, and it is efficient in day light and less energy can be collected in indoor environments.

B. *Wind Energy*

Among the various energy sources, nature provides us wind which is considered as non-polluting [8]. The main mechanism in wind-based energy is that wind turbines convert the kinetic energy of the wind into mechanical power, and generators then convert the mechanical power into electricity. [10]

Wind turbine turns propellers (that resemble blades) around a rotor. The rotor is connected to the main shaft, which spins the generator to produce electricity [10]. A special type of wind turbines, referred to as micro wind turbines, has recently emerged the research community however, implementation of wind turbines remains such a challenging task because of the size and suitable windy environments for energy harvesting to WSNs. Table 2 shows that micro-turbines are more effective when fitted with more blades, but more air speed is also required.

Specifically, [15] uses a wind generator consisting of four plastic blades horizontal-axis wind turbine, with diameter of 6.3cm and length of 7.5cm. The high number of windings of the brushless generator attached to its shaft allows harvesting significant power even at low wind speeds, which are also the most frequent ones. However, wind cannot be considered a primary energy source because of its irregular behaviour.

TABLE II. COMPARISON OF MICRO-TURBINES

Author	**Number of Blades**	**Rotor Tip Diameter (cm)**	**Air Speed (m/s)**	**Maximum Power (mW)**	**Power Density (mW/cm2)**
Federspiel *et al.* (2003) [11]	4	10	2.5	8	0.10
Priya *et al.* (2007) [12]	12	10.2	4.4	5	0.06
Rancourt *et al.* (2007) [13]	3	4.2	11.8	130	9.38
Xu *et al.* (2009) [14]	4	7.6	4.5	18	0.10

C. *Radio Frequency Energy*

The conversion of radio frequency signal into electricity is known as radio frequency energy harvesting (RFEH). Normally, converted energy could be utilized for enhancing the on-time period of WSNs nodes power source (batteries). Usually, the architecture of RFEHs has three major components, i.e. information gateways, the RF energy sources and the network nodes/device. The information gateways are called as base stations, wireless routers and relays.

Power Source could be a either Ambient RF sources (e.g., TV towers) or dedicated RF energy transmitters. Usually, the WSNs nodes can communicate with information gateways wherein information gateways and RF energy sources are supplied by fixed electric source. WSNs nodes can harvest the energy from RF sources to conduct some monitoring operations in various fields such as health monitoring system and surveillance. [16]

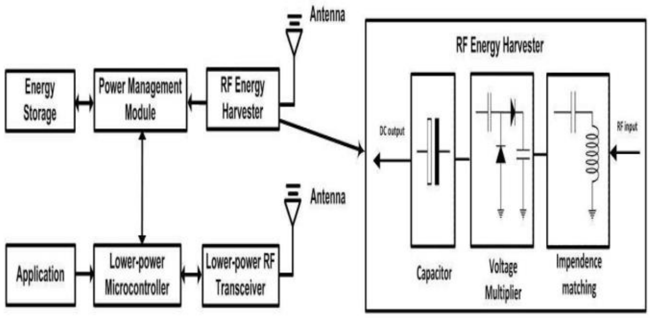

Fig. 2. Architecture of RF energy harvesting device [16].

Fig. 2. shows the block diagram of a RFEH device consists of a few components such as application, a low-power microcontroller (processing data from application), a low-power RF transceiver (information transmission or reception), an energy harvester, composed of an RF antenna, a capacitor and a voltage multiplier (to collect RF signals and convert them into electricity, a power management module and energy storage device. The RF energy harvester method is usually based on the efficiency of an antenna along with the impedance accuracy matching of an antenna with voltage multiplier. It converts the received RF signals to DC voltage. RFEH is very flexible and controls the transfer energy as per requirement of WSNs nodes. The harvested RF power is small due to the RF-to-DC low energy conversion efficiency. [18]

D. *Thermal Energy*

Thermal energy harvesting is based on techniques that exploit the Seebeck and Peltier effects. Electricity can be produced with the temperature difference for instance if temperature goes up or down then the energy can be obtained by using thermoelectricity (TE) generator. Thermal energy harvesting becomes a very interesting research area among the researcher nowadays and there are some successful industrials application using thermoelectricity (TE) generator. TE power generation is a good alternative to power source (batteries) due to its heat energy harvesting capabilities [17]. TE generator is developed by heating face of TE module and cooling the other face causing an electrical current to be generated by connected a load to the end points of the TE module, discovered by Tomas Seebeck in 1821.

The Seiko thermic watch was the first application that was based on thermal energy harvesting in a consumer product. It uses a TE generator to convert body heat into electrical energy that is used to run a wrist watch. Futhermore, this energy not only run the watch, it also charges a 4.5 mAh lithium-ion battery [18]. Commercially available thermoelectric generators require a temperature difference of 10–200 ºC [20]. However, TE has low efficiency but some significant research claim harvesting efficiency of more than 10%. [19]

E. Vibrational Energy

Usually, conversion of vibration into electricity can be performed with three approaches, i.e. piezoelectric, electromagnetic, and electrostatic. Technically, transducer is an energy to energy converter. “Piezo” is a Greek word that means pressure and “electric” refers to electricity. The basic advantage of piezoelectricity is to provide high voltage. [23] Fig. 3 illustrate that how Volture can be used to power a wireless sensor node [23].

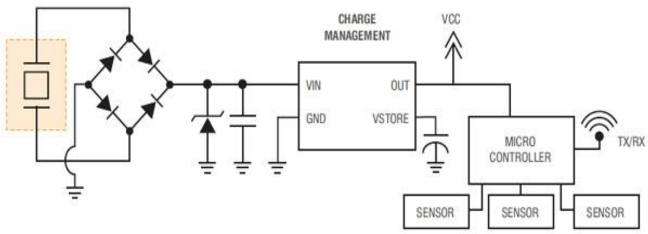

Fig. 3. Volture powering a wireless sensor node (Courtesy of Midé Technology Corporation) [23].

Piezoelectricity materials are quartz, soft and hard lead ziconate titane piezoceramics (PZT-5H and PZT5A), barium titanate (BaTiO3) and polyvinylidene fluride (PVDF) [21]. Usable output voltage is can be obtained directly from the piezoelectric effect and there is no need for multistage post processing for generating the required voltages [22]. Electromagnetic transducers, generate electricity through the relative motion of a coil and a magnet. Electrostatic transducers respond to changes due to vibration in the distance between two electrodes of a polarized capacitor. Typically, vibrational energy harvesters could be reaching from a few microwatts of several mill watts. Midé Technology Corporation makes the Volture line of piezoelectric energy harvesters. The Volture is developed to extract usable electrical energy from waste mechanical vibrations. [23]

The Volture product has numerous application such as Industrial health Monitoring Network sensors, condition based maintenance sensors, and wireless HVAC sensors.

III. Storage Devices

As mentioned above, WSN nodes can use non-chargeable or rechargeable batteries. Table 3 shows the specifications of rechargeable batteries based on lithium-ion and thin films. The coupling or combination of energy harvester device with lithium-ion or thin films recharge able battery can be implemented for increasing battery drainage period. The sole purpose of energy harvesting is to enhancing the finite life time for further longer period.

TABLE III. CHARACTERISTICS OF BATTERIES AND SUPERCAPACITORS [10].

Battery					**Super-capacitor**
	Li - ion	**Li – Po**	**Nickel Cadmium**	**Thin film**	
Operating Voltage (V)	3-3.70	3.7	1.25	3.70	1.25
Energy density (W h/l)	435	300-450	~110 - 150	<50	6
Specific energy (W h/kg)	211	150-200	40-60	<1	1.5
Self-discharge rate (%/ month)	5-10 at 25°C	1-2 at 25°C	20-30 at 25°C	0.1-1 at 20°C<2% * at 25°C	100
Cycle life (cycles)	2000	>1200	500-2000	>1000	>10.000
Temperature range (C)	-20/50	-40 to 60	-20 to 60	-20/70	-40/65

IV. Energy Harvesting Considerations for the Wearable Health-Monitoring Application

In [24] we have proposed a wearable health-monitoring system. The concept behind the work is to fit the human body with various vital signs, gesture and gait sensors of which the collected data can be (pre)processed either locally or remotely. The system builds upon a multi-hop 6LoWPAN based wireless sensor body area network to collect the data from the various sensors. The early prototype of the sensor node is shown in Figure 4.

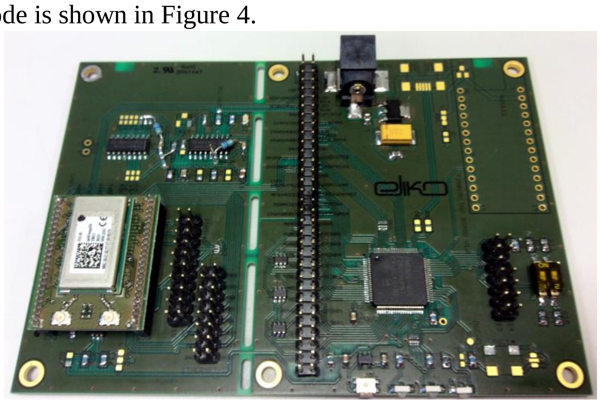

Fig. 4. Early prototype of the wearable health-monitoring sensor node. Left: wireless communication module; right: DSP module

The data are wirelessly transmitted to a gateway connected to the internet. The targeted usage includes hospitals where multiple patients can be monitored individually or in groups, private and nursing homes, as well as outdoor and urban environments. For such scenarios, energy harvesting is highly desirable since it can minimize the inconvenience that users would face is they were to replace the node batteries too often.

Fitting the human body (either on the WSN nodes or other strategic locations) with miniature solar cells could provide energy to the nodes. However, as humans are rarely static (even if sleeping in a bright environment), the level of harvested energy will greatly vary depending on the body's position. Thus, solar energy harvesting alone may not be sufficient.

RF energy harvesting can also be considered for the health-monitoring application. In many of the scenarios listed above, the user will be located in environments subject to RF waves emitted by mobile phones, Wi-Fi networks, and possible other WSN applications. Although the energy harvestable from a single RF source may be modest, multiple sources could be exploited by means of a wideband RF energy harvester.

The human body continuously radiates heat; thus placing heat-based energy harvesters on the human body could increase the autonomy of the WSN nodes. A practical difficulty is that the temperature gradient between the human body and its environment is relatively low as human either cover themselves in cold weather or use shadow or cooling devices in warm weather.

Harvesting energy from vibrations and pressure by means of piezoelectric devices may also be suitable for the above applications. Vibrations are present in most human activities; ample movements of the legs and arms (e.g. when running) can provide suitable energy levels, smaller movements (e.g. when hand-writing or typing) on provide modest energy-levels. When humans are at rest (e.g. sitting or lying), pressure may be exploited by placing piezoelectric devices between the body and the surface onto which it rests. However, as human tend to move even while sleeping, practical exploitation may be limited.

None of the energy harvesting technology presented above is ideal for the targeted wearable health-monitoring application. Thus, hybrid solutions may be used to exploit various energy sources, either simultaneously or alternatively depending on the conditions set by the environment and human activities.
Such hybrid solution include [25] that combine solar and piezoelectric devices together with an energy management circuit. Experimental results show that such hybrid approaches can multiply the level of harvested energy by three times of traditional thermal sources [26].

V. Concluding Words

Various energy harvesting technologies have been presented and their suitability for a wearable health-monitoring application has been discussed; hybrid solutions appear to be the most promising. The next step of our research effort consists in modelling these technologies, including the hybrid ones, for incorporation in a WSN simulation environment.

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