IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 2 Issue 7, July 2015.

www.ijiset.com

ISSN 2348 – 7968

Innovative Techniques To Improve The Life Time Of Wireless Sensor Networks (WSN)

[1] R. Deenadhayalan [2] Dr. S. Anandamurugan

[1]Assistant Professor, Department of Information Technology, Kongu Engineering College, Perundurai, Erode

[2]Assistant Professor (SLG), Department of Information Technology, Kongu Engineering College, Perundurai, Erode

Abstract. In recent years, wireless sensor networks (WSNs) have grown dramatically and made a great progress in many applications. But having limited life, batteries, as the power sources of wireless sensor nodes, have restricted the development and application of WSNs which often requires a very long lifespan for better performance. In order to make the WSNs prevalent in our lives, an alternative energy source is required. Environmental energy is an attractive power source, and it provides an approach to make the sensor nodes self-powered with the possibility of an almost infinite lifetime. The goal of this survey is to present a comprehensive review of the recent literature on the various possible energy harvesting technologies from ambient environment for WSNs.

Keywords: *Wireless Sensor Networks, Energy, Harvesting, Life time, Generation.*

1 Introduction

In recent years, with the development of microelectronics and wireless communication technology, WSNs, as one of the world's ten top technologies in the 21st century, are a hot research field at home and abroad for the importance in the national defense and military applications [1, 2], environment monitoring [3], healthcare [4, 5], traffic control [6], industrial monitoring [7], target tracking [8], structural health monitoring [9], and so forth. WSNs are usually composed of many low-cost low-power microsensor nodes which are spread in a certain area aiming at collecting and processing the required data and transmitting them to a base station cooperatively by a wireless communication method[11]. At present, low power consumption has almost become a core of research in WSNs like low-power MAC protocols [12, 13], routing protocols [14, 15] and transport protocols [16], and even operating systems [17] have also stressed the low power design, in order to prolong the life cycle of sensor network.

A non-rechargeable lithium battery is a promising energy storage device and the power density of it is 45 μW/cm3 for a one-year lifetime and 3.5 μW/cm3 for a ten-year lifetime [18]. However, when WSNs are requested to work for a long time, the chemical battery cannot be the only energy source in many applications where a huge number of sensors are distributed or the place is extremely difficult to access for replacing or recharging the battery is an uneconomical or impossible behavior, such as biomedical field, environmental monitoring, and military applications [19, 20]. So with the demand of exploring a new type of micro power to solve above problems, the micro environmental energy harvesting technology has emerged.

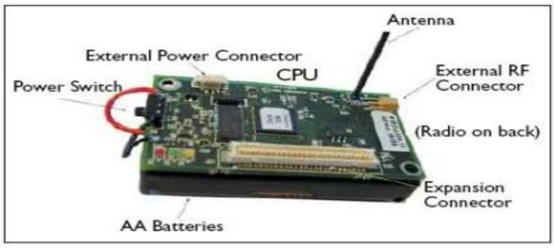
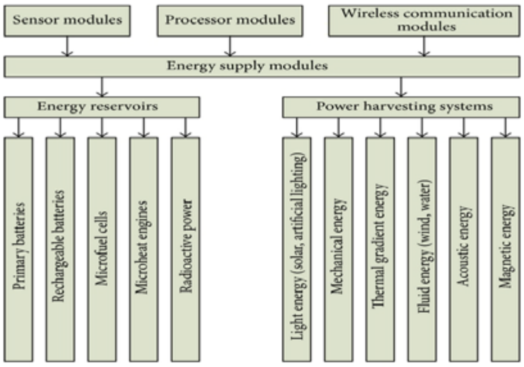


Figure 1: Sensor node



The image of the sensor node is displayed in figure 1.1.

Figure 1.2: The structure of wireless sensor nodes

Considering energy supply modules, the structure of wireless sensor nodes is shown in Figure 1.2.

Up to now, there have been some reports that the power of WSNs was provided by energy harvesting systems. For example, the solar harvesting device was tested in the alpine valleys to supply power for wireless sensor nodes. The test system consists of storage batteries, solar panels, and various control and test circuits. The test time started from the summer of 2005 and lasted for more than 100 days. The test site was chosen in the Alps for the weather conditions there are very poor as thunderstorms and rain clouds often occur. However, experimental results showed that the solar cells were able to provide a relatively stable electric power for sensor nodes [23].

The researchers of Takenaka Corporation developed a new WSN system which contains vibration energy harvesters and wireless sensors. The system is able to run without batteries and power lines for it can convert ambient mechanical vibration produced by people walking around and equipment operation into electrical energy.

2 Sources of Energy Harvesting

Energy:

Formula for calculating energy is

Energy = Power*Time ------------(1)

Unit of energy is Kwh /hr or Joule There is a variety of methods to harvest various energies in the ambient environment. The classification of energy harvesting in this paper is organized on the basis of the different forms of energy. And the energy sources reviewed in the paper include solar, mechanical, temperature gradient, dynamic fluid, acoustic, magnetic, and hybrid energy. For comparison, some examples of power outputs from energy harvesting technologies are listed in Table 1.

Table 1: Comparison of power outputs from energy harvesting technologies

Harvesting method	Power density
Solar energy—outdoors	15 mW/cm^3—bright sunny day
	0.15 mW/cm^3—cloudy day
Solar energy—indoors	10–100 μW/cm^2
Vibrations (piezoelectric—shoe inserts)	330 μW/cm^3
Vibrations (electrostatic conversion)	0.021 μW/mm^3—105 Hz
Vibrations (electromagnetic conversion)	184 μW/cm^3—10 Hz
	306 μW/cm^3—52 Hz
Thermoelectric—5°C gradient	40 μW/cm^3
Wind flow	16.2 μW/cm^3—5 m/s
Acoustic noise	3 nW/cm^3—75 dB
	960 nW/cm^3—100 dB
Magnetic field energy	130 μW/cm^3—200 μT, 60 Hz

The general structure diagram of energy harvesting system of wireless sensors is shown in Figure 2.1 with the purpose of achieving stable long-term operation [33].

3 Photovoltaics Power Generation

There are two methods to extract solar power at present. One is solar thermal power generation which is suitable for large engineering systems and not applicable in WSNs for it is not available on small or nanoscale [34]. In photovoltaic system, solar cells are used to convert sunlight into electrical power directly according to photovoltaic principle [21]. The other light such as fluorescent and infrared can also be used as the power source for solar cells [34]. At present, polycrystalline silicon solar cells possess the largest production and market share, followed by monocrystalline silicon solar cells which are suitable for conditions of high-intensity light and outdoor spectrum [35].

The energy storage device is used to store generated energy as well as buffering the power required by sensor nodes [37]. The wireless sensors can be connected to energy storage device directly for its DC characteristics. While the voltage range of each sensor node may not be the same and some sensors may be very sensitive to the change of voltage supply, then the output voltage needs to be regulated by DC-DC converter [38]. However, sometimes this method is not advisable with considering the simplicity and efficiency of energy harvesting system. The additional regulation may also be required between sensor and energy storage device to ensure that the sensor node works with a stable and safe voltage.

Solar energy has been more widely considered for WSNs which consume several mV of energy as it is common and accessible energy in the majority of deployment environments and can be easily tapped. While it is designed as a power source for WSNs, the first thing which we must consider is the power supply requirements of WSNs.The solar cells, power conditioning features, and the chemistry and capacity of energy storage components used to store the harvested energy. With the cost of optoelectronic components declining, it has become a reasonable solution to utilize solar energy source for WSNs. At present solar cells with high efficiency are available in market and have several remote sensing and wireless applications. And the photovoltaic technology has developed into particles deposition on the photosensitive substrate from the initial silicon manufacturing. Recently, researchers have made a lot of breakthroughs of micro solar cells and some of them are shown in the following. The company of Kyosemi developed a micro spherical solar cell called Sphelar which is a revolutionary transformation compared to the previous solar cell.

Canadian scientists developed a new kind of efficient full spectrum solar cell with tandem-type connection based on colloidal quantum dots (CQD) and the theoretical conversion efficiency is as high as 42%. This progress is helpful to develop a new battery with the thickness of only one percent of the current commercial thin-film solar cells. At present, researchers have developed a thin-film battery with thickness of a few tenth of nanometer.

Recently, the Australian and Japanese scientists invented a solar cell which is thinner than spider web. This ultrathin solar cell is composed of electrodes which are embedded in the plastic tab and the thickness is only 1.9 microns which is equivalent to one tenth of the current thinnest solar battery. The solar panel is modular and can be utilized on any scale to achieve the power desired. It can still generate some power when there is dense cloud in sky for the ability of convert emitted light. In addition, the panels require almost no maintenance and have a typical lifetime of about 20 years [34].

4 Mechanical Energy Harvesters

The mechanical energy is generated when an object is subjected to some movement or mechanical deformation and it can be converted into electrical energy by several methods including piezoelectric, electrostatic, and electromagnetic conversion.

Table 2: The energy harvesting method corresponding to different vibration sources.

The form of vibration sources	Energy harvesting method
Force excitation	Piezoelectric energy harvesting method
Velocity excitation	Electromagnetic energy harvesting method
Displacement excitation	Piezoelectric electrostatic energy harvesting method

The vibration is the most prevalent energy source for it is available in many environments including buildings, roads, bridges, vehicles, ships, and other kinds of production and living facilities. And in the biomedical sciences, the mechanical energy harvesters can also be utilized to provide energy for biological sensors which are used to real-time monitor parameters like blood pressure and blood-sugar levels, and so forth, of human or animals by taking advantage of body pulse and blood current.

4.1 Piezoelectric Energy Harvesters

With the improvement of piezoelectric materials, piezoelectric properties, and the use of highly integrated, low-power electronic devices, the piezoelectric harvesting technology has received extensive attention in recent years. And it is an inherent property of piezoelectric materials that generate electricity when pressure is applied. Piezoelectric transduction is generally well suited to the reciprocating nature of the motions instead of rotating systems.

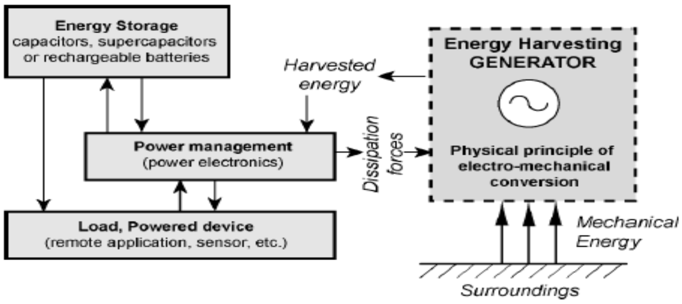


Figure 3: Schematic of Energy Harvesting System

Piezoelectric materials mainly include piezoelectric monocrystal, piezoelectric ceramics, piezoelectric polymers, and piezoelectric composites. At present, piezoelectric ceramic PZT is the most commonly used piezoelectric materials for the piezoceramics have the advantages of mature manufacturing process, low cost, large electromechanical coupling constants, and high energy conversion rate. But piezoelectric ceramic PZT is fragile and unable to bear large strain, and it is easy to produce fatigue crack and brittle fracture on the impact of high-frequency cyclic load. Another commonly used piezoelectric material is polyvinylidene fluoride (PVDF). Compared to piezoelectric ceramic PZT, PVDF has smaller electromechanical coupling constants, but it has advantages of good flexibility, high mechanical strength, good fatigue resistance, and chemical stability and is suitable for the application with under the high-frequency periodic load.

4.2 Electrostatic (Capacitive) Energy Harvesting

ISSN 2348 – 7968

Electrostatic harvesting is based on the principle of changing capacitance of vibration-dependent capacitors [39]. Vibrations split the plates of a charged variable capacitor, and mechanical energy is converted into the form of electrical energy. It harvesters require a polarization source to work and to change mechanical energy from vibrations into electricity. The polarization source should be in the order of some hundreds of volts; this greatly makes problem of the power management circuit. A further solution consists in using electrets, which are electrically charged dielectrics an able to remain the polarization on the capacitor for years. It is possible to settle in structures from classical electrostatic induction generators, which also remove energy from variable capacitances, for this purpose. The resulting devices are self-biasing, and can straightforwardly charge batteries, or can produce exponentially increasing voltages on storage capacitors, from which energy can be periodically, pull out by DC/DC converters.

4.3 Electromagnetic Energy Harvesting

Electromagnetic Energy Harvesting is based on the well-known principle of electromagnetic induction which is defined as induced electromotive force which will be generated in a conductor when the magnetic flux is changing around it. The electromagnetic vibration energy harvesters can be simply packaged to reduce the risk of corrosion and eliminate the temperature limit.

Table 4: Performance parameters of typical magnetic materials

Material	B/mT	(BH)max/(kJ/m^3)	Hc	Tc/°C	Max. operating temperature/°C	Density/(kg/m^3)
Ceramics	100	26	High	460	250	4980
Alnico	130	42	Low	860	550	7200
SmCo (2:17)	350	208	High	750	300	8400
NdFeB (N38H)	450	306	High	320	120	7470

5 Thermoelectric Generators

The temperature difference between the two ends of semiconductor PN junction is used to generate power by micro thermoelectric power generation system. Thermoelectric materials have three temperature-dependent properties: Seebeck coefficient, thermal conductivity, and electrical conductivity. There are many sources of waste heat which can be used around us, such as geothermal, industrial waste heat, engine exhaust and the heat of sun.

The conversion efficiency of current thermoelectric generators (TEGs) is commonly between 6% and 11%. The efficiency of TEGs is approximately proportional to temperature difference when it is small while both of thermoelectric materials and temperature difference have a strong influence on the output voltage, and the generated voltage is proportional to the number of thermoelectric elements and the temperature difference when the thermoelectric materials is selected. Because it is difficult to maintain a

ISSN 2348 – 7968

significant temperature gradient on a small device, the small available temperature difference between the surfaces of the TEG, commonly no higher than 10°C, and the micro size of the devices make the output power and the conversion efficiency very limited.

6 Dynamic Fluid Energy Harvesting

Dynamic fluid energy includes wind and flowing water power. The kinetic energy of fluid can be harvested by two methods. The first one generates electricity by mechanical parts such as micro turbine systems.

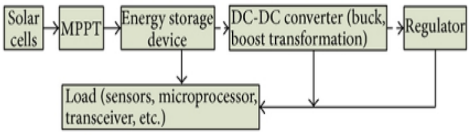


Figure 4: The general block diagram of solar energy harvesting system for wireless sensors

The second one uses nonmechanical parts that works the same as the mechanical energy harvesting technology for the flowing wind or water induces mechanical vibration which can be converted to electricity by piezoelectric, electrostatic, or electromagnetic principles.

6.1. Micro Wind Harvester

The ambient air flow or forced convection can also be an energy source for wireless autonomous sensor nodes in outdoor, remote, or inaccessible locations. The existing methods of wind energy harvesting include micro wind turbines, micro windbelt generators, piezoelectric wind harvesters and electromagnetic wind generators. In addition, the rotating components of conventional turbines, uch as bearings, suffer from fatigue and wear.

6.2. Flowing Water Energy Harvesting

The flowing water contains kinetic energy due to the water pressure fluctuation, and it can be converted into electrical energy by energy harvesters. Flowing water is a renewable, pollution-free, continuous, and dependable energy source for wireless sensor nodes. For hydropower can be developed in any size and any scale, it is applicable in WSNs [34].
Sun and Hu developed an electromagnetic vibratory generator based on impact of water current.

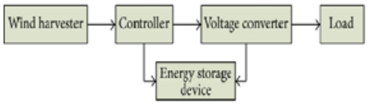


Figure 5: The composition block diagram of micro wind power system

Pobering and Schwesinger presented two types of energy harvester, a flag-shaped piezoelectric polymer harvester and a microstructured piezobimorph generator, to convert the kinetic energy of flowing water into electrical energy. While the flow-induced vibration energy harvester has a micro size, it needs further research to increase the conversion efficiency and optimize the generated power to be appropriate for powering wireless sensor nodes.

7 The Acoustic Energy

The acoustic energy can be used by people like other forms of energy. When sound wave spreads to the surface of an object, it will cause vibration of the object. It was measured that the generated power is up to 100 kW when the noise of jet is 160 dB.
The common elements of acoustic energy systems include an input mechanical power spectrum, an effective acoustic impedance matching, a piezoelectric or biased electrostrictive transducers converting the input mechanical energy into electrical energy and a matched electrical load.

8 Magnetic Energy Harvesting

Magnets vibrating on a cantilever are responsive to even small vibrations and generate micro currents by moving comparative to conductors due to Faraday's law of induction [39]. Sensors in inaccessible places can now produce their own power and transmit data to outside receivers. One of the major restrictions of the magnetic vibration energy harvester developed at University of Southampton is the size of the generator, in this case approximately one cubic centimeter, which is much too large to integrate into today's mobile technologies. The complete generator with circuitry is a massive 4 cm by 4 cm by 1 cm nearly the similar size as some mobile devices such as the iPod nano. Additional drop in the dimensions are possible through the combination of fresh and additional stretchy materials as the cantilever beam component. In 2012 a group at Northwestern University developed a vibration-powered generator out of polymer in the form of a spring. This device was able to intention the equal frequencies as the University of Southampton groups silicon based device but with one third the size of the beam component.

Business successful vibration energy harvesters have been developed from the early University of Southampton prototypes by Perpetuum. These have to be sufficiently large to generate the power required by Wireless Sensor Nodes (WSN) but in M2M applications this is not normally an issue. These harvesters are now being supplied in large volumes to power wsn's made by companies such as GE and Emerson and also for train bearing monitor systems made by Perpetuum. Overhead power line sensors can use magnetic induction to harvest energy straight from the conductor they are monitoring.

9 Hybrid Power Source

In mainly the electrified transportation systems, where only batteries are operate as energy storage system, usually batteries are personalized for the power rather than energy. In recent technologies do not offer a battery proficient of high enough power densities without over-sizing it. Moreover, battery lifetime can reduce drastically if it is subjected to immediate charge/discharge pulses or fast variable currents. This results in increasing the size, cost and size of the battery pack or decrease the battery life and thermal runaway troubles [40].

In order to offer more efficient propulsion, without sacrificing the performance, increasing the fuel consumption, and over-sizing the battery, more than one energy storage devices with balancing characteristics can be used in electric traction systems. In a hybrid ESS, proper power budgeting based on the specific characteristics of energy sources would result in higher efficiency, longer life time of energy sources, as well as reducing their size and cost. The energy sources should be able to store, supply, bring back high power pulses and supply the fixed demands of the vehicle. A hybrid topology collected of a high power density component such as an ultra-capacitor (UC) and high energy density component such as a rechargeable battery offers a concession of both.

10 Conclusion

This paper gives a comprehensive introduction of the various possible environmental energy harvesting technologies and the selection of which should be suitable for the actual applications and working environments of WSNs. (1)As mentioned above, there are a lot of different forms of energy in the environment. (2)Up to now, there is a great distance between the existing energy harvesting technologies and the mass commercial production for all kinds of environmental energy harvesting technologies are still not mature, and the output power and energy conversion efficiency are low. (3)The size of energy harvesting system should be reduced as much as possible for the strict requirements of sensor nodes in many applications.

Miniaturization is the development tendency of the future energy harvesting system. (4)It is essential to combine the structure design and key circuits with the scheduling and agreement based on power-aware of wireless sensor nodes to prolong the sensor nodes life. (5)It is a necessity to integrate the energy harvesting method, power management strategy, battery recharging, and new communication standards.

References

[1]. K. A. Kumar, "IMCC protocol in heterogeneous wireless sensor network for high quality data transmission in military applications," in Proceedings of the 1st International Conference on Parallel, Distributed and Grid Computing (PDGC '10), pp. 339–343, October 2010.

[2]. F. T. Jaigirdar, M. M. Islam, and S. R. Huq, "An efficient and cost effective maximum clique analysis based approximation in military application of wireless sensor network," in Proceedings of the 14th International Conference on Computer and Information Technology (ICCIT '11), pp. 85–90, December 2011.

[3]. P. Padhy, K. Martinez, A. Riddoch, J. Hart, and H. Ong, "Glacial environment monitoring using sensor networks," in Proceedings of the Conference on Real-World Wireless Sensor Networks, 2005.

[4]. J. A. Stankovic, Q. Cao, T. Doan, et al., "Wireless sensor networks for in-home healthcare: potential and challenges," in Proceedings of the the High Confidence Medical Device Software Systems Workshop, 2005.

[5]. G. Virone, A. Wood, L. Selavo et al., "An assisted living oriented information system based on a residential wireless sensor network," in Proceedings of the 1st Transdisciplinary Conference on Distributed Diagnosis and Home Healthcare (D2H2 '0606), pp. 95–100, April 2006.

[6]. B. Płaczek, "Selective data collection in vehicular networks for traffic control applications," Transportation Research Part C: Emerging Technologies, vol. 23, pp. 14–28, 2012.

[7]. M. R. Akhondi, A. Talevski, S. Carlsen, and S. Petersen, "Applications of wireless sensor networks in the oil, gas and resources industries," in Proceedings of the 24th IEEE International Conference on Advanced Information Networking and Applications (AINA '10), pp. 941–948, April 2010.

[8]. N. Hubbell and Q. Han, "DRAGON: detection and tracking of dynamic amorphous events in wireless sensor networks," IEEE Transactions on Parallel and Distributed Systems, vol. 23, no. 7, pp. 1193–1204, 2012.

[9]. A. Elancheziyan, J. C. De Oliveira, and S. Weber, "A new system for controlled testing of sensor network applications: architecture, prototype and experimental evaluation," Ad Hoc Networks, vol. 10, no. 6, pp. 1101–1114, 2012..

[10]. J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," Computer Networks, vol. 52, no. 12, pp. 2292–2330, 2008.

[11]. Y.-T. Yong, C.-O. Chow, J. Kanesan, and H. Ishii, "A survey on design of self-powered wireless sensor network," in Proceedings of the International Conference for Technical Postgraduates (TECHPOS '09), pp. 1–5, December 2009.

[12]. A.B. Nacef, S.-M. Senouci, Y. Ghamri-Doudane, and A.-L. Beylot, "A cooperative low power Mac protocol for wireless sensor networks," in Proceedings of the IEEE International Conference on Communications (ICC '11), pp. 1–6, June 2011.

[13]. S. Dash, A. R. Swain, and A. Ajay, "Reliable energy aware multi-token based MAC protocol for WSN," in Proceedings of the 26th IEEE International Conference on Advanced Information Networking and Applications (AINA '12), pp. 144–151, March 2012.

[14]. G.-G.Mplemenos and I. Papaefstathiou, "Fast and power-efficient hardware implementation of a routing scheme for WSNs," in Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC'12) pp.1710–1714,April 2012.

[15]. L. Tao and L. Feng, "Power-efficient clustering routing protocol based on applications in wireless sensor network," in Proceedings of the 5th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM '09), pp. 1–6, September 2009.

[16]. R. Bhuvaneswari and B. J. Bejoy, "Energy efficient reliable transport protocol for re-tasking in wireless sensor network," in Proceedings of the National Conference on Innovations in Emerging Technology (NCOIET '11), pp. 1–6, February 2011.

[17]. H.-Y. Zhou, F. Wu, and K.-M. Hou, "An event-driven multi-threading real-time operating system dedicated to wireless sensor networks," in Proceedings of the International Conference on Embedded Software and Systems (ICESS '08), pp. 3–12, July 2008.

[18]. S. Roundy, P. K. Wright, and J. Rabaey, "A study of low level vibrations as a power source for wireless sensor nodes," Computer Communications, vol. 26, no. 11, pp. 1131–1144, 2003.

[19]. V. Raghunathan, S. Ganeriwal, and M. Srivastava, "Emerging techniques for long lived wireless sensor networks," IEEE Communications Magazine, vol. 44, no. 4, pp. 108–114, 2006.

[20]. J. Wu and G. Zhou, "A new ultra-low power wireless sensor network with integrated energy harvesting, data sensing, and wireless communication," in Proceedings of the IEEE International Conference on Communications (ICC '11), pp. 1–5, 2011.

[21]. R. J. M. Vullers, R. van Schaijk, I. Doms, C. Van Hoof, and R. Mertens, "Micropower energy harvesting," Solid-State Electronics, vol. 53, no. 7, pp. 684–693, 2009.

[22]. T. V. Prabhakar, S. Devasenapathy, H. S. Jamadagni, and R. V. Prasad, "Smart applications for energy harvested WSNs," in Proceedings of the 2nd International Conference on Communication Systems and Networks (COMSNETS '10), pp. 1–7, January 2010.

[23]. C. Alippi and C. Galperti, "An adaptive system for opimal solar energy harvesting in wireless sensor network nodes," IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 55, no. 6, pp. 1742–1750, 2008.

[24]. S. W. Arms, C. P. Townsend, D. L. Churchill et al., "Energy harvesting, wireless, structural health monitoring

and reporting system," Materials Forum, vol. 33, pp. 220–234, 2008.

[25]. N. S. Shenck and J. A. Paradiso, "Energy scavenging with shoe-mounted piezoelectrics," IEEE Micro, vol. 21, no. 3, pp. 30–42, 2001.

[26]. G.-J. Sheu, S.-M. Yang, and T. Lee, "Development of a low frequency electrostatic comb-drive energy harvester compatible to SoC design by CMOS process," Sensors and Actuators, A: Physical, vol. 167, no. 1, pp. 70–76, 2011.

[27]. Ö. Zorlu, E. T. Topal, and H. Külah, "A vibration-based electromagnetic energy harvester using mechanical frequency up-conversion method," IEEE Sensors Journal, vol. 11, no. 2, pp. 481–488, 2011.

[28]. Ö. Zorlu, E. T. Topal, and H. Külah, "An electromagnetic micro power generator for low-frequency environmental vibrations based on the frequency up conversion technique," IEEE Journal of Microelectromechanical Systems, vol. 11, no. 2, pp. 481–488, 2011.

[29]. S. P. Beeby, R. N. Torah, M. J. Tudor et al., "A micro electromagnetic generator for vibration energy harvesting," Journal of Micromechanics and Microengineering, vol. 17, no. 7, pp. 1257–1265, 2007.

[30]. D. Pescovitz, 2002, The Power of Small Tech. Smalltimes. 2, 1.

[31]. D. Vatansever, R. L. Hadimani, T. Shah, and E. Siores, "An investigation of energy harvesting from renewable sources with PVDF and PZT," Smart Materials and Structures, vol. 20, no. 5, 2011.

[32]. K. Tashiro, H. Wakiwaka, S.-I. Inoue, and Y. Uchiyama, "Energy harvesting of magnetic power-line noise," IEEE Transactions on Magnetics, vol. 47, no. 10, pp. 4441–4444, 2011.

[33]. J. M. Gilbert and F. Balouchi, "Comparison of energy harvesting systems for wireless sensor networks," International Journal of Automation and Computing, vol. 5, no. 4, pp. 334–347, 2008.

[34]. S. R. K. Tabbakh, R. Maarefdoust, N. C. Kyun, and B. Mohd Ali, "Environmental taxonomy of power scavenging techniques for autonomous self powered wireless sensors," in Proceedings of the Asia Pacific Conference on Circuit and System (APCCAS '10), pp. 1031–1034, December 2010.

[35]. S. Roundy, D. Steingart, L. Frechette, P. Wright, and J. Rabaey, Power Sources for Wireless Sensor Networks, Lecture Notes in Computer Science, Springer, 2004.

[36]. D. Brunelli, L. Benini, C. Moser, and L. Thiele, "An efficient solar energy harvester for wireless sensor nodes," in Proceedings of the Design, Automation and Test in Europe (DATE '08), pp. 104–109, March 2008.

[37]. J. Gakkestad and L. Hanssen, "Powering wireless sensor networks nodes in Northern Europe using solar cell panel for energy harvesting," in Proceedings of the 4th IFIP International Conference on New Technologies, Mobility and Security (NTMS '11), pp. 1–5, February 2011.

[38]. Gongbo Zhou, Linghua Huang, Wei Li, and Zhencai Zhu, "Harvesting Ambient Environmental Energy for Wireless Sensor Networks: A Survey", 2014

[39]. https://en.wikipedia.org/wiki/Energy_harvesting

[40]. http://khaligh.umd.edu/hybrid-energy-storage-systems