A review on energy harvesting and storage for rechargeable wireless sensor networks

Tony 1,2* and Lely Hiryanto 1,2
1 School of Electrical Engineering, Computing & Mathematical Sciences, Curtin University
2 Faculty of Information Technology, Universitas Tarumanagara Jakarta 11440, Indonesia

tony@postgrad.curtin.edu.au

Abstract. Wireless sensor networks with battery-operated nodes have the limitation in the energy availability at each node. One visible solution is to add the nodes with energy harvesting capability. By harnessing energy from the environment or other sources, the nodes can prolong its operation. This paper provides a brief review of energy harvesting systems – protocol, energy sources, and storage technologies. The study also discusses some opportunities of further research on energy harvesting networks.

1. Introduction

Wireless sensor networks (WSNs) consists of large number of embedded devices or sensor nodes with ability to sense and collect data then send it to base stations (sink) via wireless [1]. In [2], Akylidiz et.al investigate WSNs technology and various potential applications, such as smart home [3], habitat monitoring [4], health [5], military [6], industry [7], and commercial applications [8]. Due to their rapid development, the use of WSNs grows drastically in the future.

Generally, each sensor node comprises of four basic subsystem [9]: (i) sensing to gain data, (ii) processing to process data, (iii) wireless communication to transmit/receive data, and (iv) power (battery with finite capacity) to activate the nodes. For most WSNs implementations, it is complicated and unfeasible to recharge or replace the batteries due to the deployment of the nodes in hostile and difficult-to-reach locations or due to the vast number of nodes. Based on the battery type utilized by their nodes, WSNs can be categorized into: rechargeable and non-rechargeable. The non-rechargeable WSNs will die once the batteries are exhausted since each battery has limited energy budget. On the other hand, the rechargeable WSNs (rWSNs) employ batteries which can be recharged by harvesting energy from wind, solar, and wireless power transfer technique [10], e.g. Witricity [11]. By equipping the nodes with energy harvesting capability, rWSNs potentially can be autonomous [12], born-again or reincarnation [13], and even perpetual or immortal [14].

Energy harvesting technique exploits energy from ambient environment or other energy sources and transforms it to electrical energy to activate the nodes in rWSNs [9], [15]. The harvested energy can power the nodes continually if it is large and periodically available [15]. As a result, energy harvesting offers a promising solution to prolong the lifetime of energy-constrained rWSNs [16].
As contributions of this study, we present brief review of energy harvesting techniques, including:

- energy harvesting usage protocols,
- energy sources for harvesting energy,
- energy storage technologies, and
- open research challenges on energy harvesting.

The rest of the paper is organized as follows. In Section 2, we present the energy harvesting usage protocols. Energy harvesting sources are reviewed in Section 3. Section 4 presents the storage technology in energy harvesting. We point out the open research issues in Section 5 and conclude this paper in Section 6.

2. Energy Harvesting Usage Protocols

There are three energy harvesting usage protocols generally used: (i) Harvest-Use (HU), (ii) Harvest-Store-Use (HSU), and (iii) Harvest-Use-Store (HUS) [17] - see Fig. 1.

- HU [15]: The harvested energy at slot $t$ directly power the sensor nodes at slot $t$. Unused energy is not stored as there is no buffer or storage for later use.
- HSU [15]: The harvested energy at slot $t$ is first stored in the storage for used in the subsequent slots, i.e. the harvested energy in slot $t$ can only be used starting at slot $t+1$. The storage can be single-stage or double stage. If the primary storage is exhausted, then the secondary storage will backup storing energy.
- HUS [17]: The harvested energy that is temporary stored in a supercapacitor at slot $t$ can be used by the sensor nodes immediately, i.e., also at slot $t$. Unused energy harvested at slot $t$ is stored in the storage for future use. This protocol offers better performance with higher achievable harvesting rate and lower energy loss.

![Energy harvesting usage protocols](image)

**Figure 1.** Energy harvesting usage protocols

3. Energy Harvesting Sources

A major component of energy harvesting architecture is the energy source. Energy harvesting sources have diverse characteristics in terms of controllability and predictability [15]. A *controllable* energy source can supply the harvested energy whenever needed. In contrast, *uncontrollable* energy sources harvest the energy whenever available. On the other hand, a *predictable* energy source can forecast the availability of harvested energy and show the next recharge cycle. Furthermore, energy harvesting sources can be classified into two categories [9]: (i) ambient sources and (ii) external sources. Ambient sources provide energy with no cost as always available in the environment. But external sources are dispersed explicitly in the environment. Furthermore, those categories are then divided as shown in Fig. 2.
3.1. Ambient Sources
The ambient energy sources, e.g. solar, thermal, wind, and radio frequency (RF) can be categorized into four main types: (i) solar/light, (ii) thermoelectric, (iii) motion/vibration and (i) electromagnetic (EM) radiation. Table 1 shows the characteristics and power density or watts per unit volume of ambient environment.

| Ambient Sources | Types            | Characteristics                      | Power Density              |
|-----------------|------------------|--------------------------------------|----------------------------|
| Solar           | Solar/light      | Uncontrollable, predictable          | 100 mW/cm²                 |
| Illumination    | Solar/light      | Partially controllable, predictable  | 10 – 100 µW/cm²            |
| Thermal         | Thermoelectric   | Uncontrollable, unpredictable        | 10 µW/cm² – 1 mW/cm²       |
| Wind            | Motion/vibration | Uncontrollable, unpredictable        | 100 mW at speeds 2 – 9 m/s |
| Car engine      | Motion/vibration | Controllable, predictable            | 30 mW                     |
| Blood vessel    | Motion/vibration | Controllable, predictable            | 1 µW                      |
| Knee bending    | Motion/vibration | Controllable, predictable            | 7 W                       |
| EM induction    | EM radiation     | Controllable, predictable            | high efficiency ≥80%       |
| Ambient RF      | EM radiation     | Uncontrollable, unpredictable        | 0.2 nW/cm² – 1 µW/cm²      |
| Dedicated RF    | EM radiation     | Partially controllable, partially predictable | 5 µW at transmit power 4 W, distance 15 m |
3.2. External Sources
There are two types of external sources [9]: (i) mechanical-based and (ii) human-based energy harvesting. The mechanical-based energy harvesting can derive energy from vibration, pressure, and stress-strain. However, it will require Mechanical-to-Electrical Generator (MEEG) that utilize electromagnetic, electrostatic or piezoelectric to scavenge energy. On the other hand, human-based energy harvesting consists of activity based and physiological based energy harvesting. Wireless Body Area Network (WBAN) is the recently human-based energy harvesting applications [18]. Table 2 shows the characteristics of external sources energy harvesting.

| External Sources | Types    | Characteristics          |
|------------------|----------|--------------------------|
| Vibration        | Mechanical | Unpredictable, controllable |
| Pressure         | Mechanical | Unpredictable, controllable |
| Stress-strain    | Mechanical | Unpredictable, controllable |
| Activity         | Human     | Unpredictable, controllable |
| Physiological    | Human     | Unpredictable, uncontrollable |

4. Energy Storage
Storage technology is the vital part of energy harvesting systems. Thus, it is important to choose the proper storage technique and recharge technology. As discussed in the previous section, the storage component may be single or double stage. Primary storage provides the energy to the sensor nodes. When the energy in the primary component is depleted, the secondary storage will be used. Table 3 shows the primary and secondary energy storage technologies.

| Storage     | Energy (J/cm³) |
|-------------|----------------|
| Primary     | 1200 - 3780    |
|             | Rechargeable battery 650 - 1080 |
|             | Capacitor 1 - 3 |
| Secondary   | 10 - 100       |
|             | Supercapacitor 1000 - 3500 |
|             | Fuel cell 1000 - 3350 |
|             | Heat engine 1000 - 2000 |
|             | Betavoltaic cell |

There are different types of rechargeable batteries whose characteristics are dependent on their internal chemistries to power the energy harvester [21]. Several rechargeable technologies are Sealed Lead Acid (SLA), Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), Lithium ion (Li-ion), and Lithium polymer (Li-polymer). The specification of existing rechargeable batteries is given in Table 4.
Table 4. Comparisons of rechargeable batteries [15], [20]

| Specifications                  | SLA | NiCd | NiMH | Li-ion | Li-polymer |
|---------------------------------|-----|------|------|--------|------------|
| Nominal voltage (V)             | 6   | 1.2  | 1.2  | 3.7    | 3.7        |
| Capacity (mAh)                  | 1300| 1100 | 2500 | 740    | 930        |
| Weight Energy Density (Wh/kg)   | 26  | 42   | 100  | 165    | 156        |
| Power Density (W/kg)            | 180 | 150  | 250-1000 | 1800   | 3000       |
| Self-discharge per month (%)    | 20  | 10   | 30   | <10    | <10        |
| Charge-discharge efficiency (%) | 70-92| 70-90| 66   | 99.9   | 99.8       |

5. Open Research Issues
Rechargeable Wireless Sensor Networks (rWSNs) are important technology for the Internet of Things (IoT). In this section, we address several open research issues in energy harvesting techniques for rWSNs [9], [17].

1) **Generic Harvester**: A generic energy harvester which can harvest energy from multiple sources is required to power the sensor nodes so that the energy storage is not needed.

2) **Miniaturization**: A small-scale energy harvesting system that offers economically solution is required to generate sufficient energy to activate the sensor nodes.

3) **Protocol Adaptation**: Routing protocols have to adapt to provide the harvested energy in the network.

4) **Efficient Prediction Techniques**: Research community should pay more attention to extend the energy efficient prediction algorithms to improve power management.

5) **Simulation Environments**: There is no exist simulation environment which can evaluate energy harvesting systems in rWSNs.

6) **Energy-Efficient Reliable Systems**: The more reliable and ultra energy efficient sensor nodes are required to minimize the amount of energy consumption and the size of energy harvesting system.

7) **Energy Storage**: The objective of energy harvesting systems for rWSNs is to replace the storage with an autonomous energy harvesting rWSNs that only depends on the harvested energy from the ambient environment or external sources.

8) **Fundamental Limits of Energy Harvesting Channel Capacity**: The energy harvesting channel capacity for finite battery capacity is an open research challenge.

9) **Energy Harvesting at Receiver Side**: Most of the energy scheduling problems are solved for energy harvesting transmitter. The study of receiver-side energy harvesting is an interesting issue.

10) **Energy Harvesting Models and Combination of Heterogeneous Energy Sources**: Energy harvesting models are important for the energy scheduling in sensor nodes communication. While a model that combine heterogeneous energy sources is another research direction because energy harvesting rWSNs can use multiple energy sources to recharge the battery.

11) **Robust Designs with Imperfect Knowledge**: Robust designs are required to encounter the imperfection in energy harvesting rWSNs.

12) **Multiple Antenna Techniques**: The use of multiple antennas in energy harvesting rWSNs is a new research issue and provides various energy optimization problems.

13) **Security in RF Energy Harvesting**: This is a challenging security problem that needs more investigation to ensure the security of signal transmission and reception.

14) **Energy Harvesting Networks with Multiple Nodes**: There are still some problems in optimizing the performance of energy harvesting networks with multiple nodes.

15) **Energy Harvesting for Activity Recognition**: The use of energy harvesting for activity recognition is an open research challenge in energy harvesting networks.
6. Conclusion
The ability of rWSNs to scavenge energy from the environment or external sources can extend the lifetime of the nodes. In this paper, we reviewed some aspects of energy harvesting systems, such as usage protocols, types of energy harvesting sources, and energy storage technologies. Further, we showed various challenges in energy harvesting communications and networks. We hope this discussion will motivate further research on the applications of energy harvesting.

7. Acknowledgments
The authors acknowledge Dr. Sieteng Soh for giving the idea of this paper. The first author also acknowledges support from Indonesia Lecturer Scholarship (BUDI) by Indonesia Endowment Fund for Education (LPDP). This scholarship is a collaboration between the Ministry of Research, Technology, and Higher Education with the Ministry of Finance, Republic of Indonesia. The second author acknowledges Australia Awards in Indonesia. Australia Awards are international scholarships funded by the Australian Government offering the next generation of Indonesian leaders an opportunity to undertake study, research and professional development.

8. References
[1] Aboelaze M and Aloul F 2005 Proc. 2nd IFIP Int. Conf. Wireless Optical Commun. Netw. (Dubai)
[2] Akyildiz I F, Su W, Sankarasubramaniam Y and Cayirci E 2002 Comput. Netw. 38 4 pp 393-422
[3] Gomez C and Paradells J 2010 IEEE Commun. Mag. 48 6 pp 92-101
[4] Mainwaring A, Polastre J, Szewczyk R, Culler D and Anderson 2002 Proc. 1st ACM Int. Workshop Wireless Sensor Netw. Applicat. (Atlanta) pp 88-97
[5] Ko J, Lu C, Srivastava M B, Stankovic J A, Terzis A and Welsh M 2010 Proc. IEEE 98 11 pp 1947-1960
[6] Durisic M P, Tafa Z, Dimic G and Milutinovic V 2010 Proc. Mediterranean Conf. Embedded Computing (Bar)
[7] Khakpour K and Shenassa M H 2008 Proc. 3rd Int. Conf. Inform. Commun. Technologies: From Theory to Applicat. (Sydney)
[8] Wheeler A 2007 IEEE Commun. Mag. 45 4 pp 70-77
[9] Shaikh F K and Zeadally S 2016 Renewable and Sustainable Energy Reviews 55 pp 1041-1054
[10] Bi S, Zeng Y and Zhang R 2016 IEEE Wireless Commun. 23 2 pp 10-18
[11] Karalis A, Joannopoulos J D and Soljacic M 2008 Annals of Physics 323 11 pp 34-48
[12] Vullers R J M, Schaijk R V, Visser H J, Penders J and Hoof C V 2010 IEEE Solid State Circuits Mag. 2 2 pp 2938
[13] Prasad R V, Devasenapathy S, Rao V S and Vazifehjan D 2014 IEEE Commun. Surv. Tuts. 16 1 pp 195213
[14] Watfa M K, Al-Hassanieh H and Salmen S 2008 Proc. Int. Conf. Intelligent Sensors, Sensor Netw. Inform. Process. (Sydney) pp 523-528
[15] Sudevalayam S and Kulkarni P 2011 IEEE Commun. Surveys Tuts. 13 3 pp 443-461
[16] Atallah R, Khabbaz M and Assi C 2016 IEEE Wireless Commun. 23 2 pp 70-77
[17] Ku M-L, Li W, Chen Y and Liu K J R 2016 IEEE Commun. Surveys Tuts. 18 2 pp 1384-1412
[18] Akhtar F and Rehmani M H 2017 IT Professional 19 2 pp 32-40
[19] Tuna G and Gungor V C 2016 Energy harvesting and battery technologies for powering wireless sensor networks (Industrial Wireless Sensor Networks) ed R Budampati and S Kolavennu (Woodhead Publishing) pp 25-38
[20] Taneja J, Jeong J and Culler D 2008 Proc. 7th IEEE Int. Conf. Inform. Process. Sensor Netw. pp 407-418 [21] Knight C, Davidson J and Behrens S 2008 Sensors 8 12 pp 8037-8066