Proceedings of the International Conference on Intelligent Sustainable Systems (ICISS 2017)
IEEE Xplore Compliant - Part Number:CFP17M19-ART, ISBN:978-1-5386-1959-9

Energy Harvesting in IoT Devices: A Survey

Neha Garg
Computer Engineering Department
National Institute of Technology
Kurukshetra, India
Nehagarg702@gmail.com

Ritu Garg
Computer Engineering Department
National Institute of Technology
Kurukshetra, India
Ritu.59@nitkkr.ac.in

***Abstract*— Normally, IoT devices are powered by the batteries. As the lifetime of battery is limited thus, there is strong need of self-powered devices or alternative sources of energy to continuously power the IoT devices. For the same purpose energy harvesting techniques are used nowadays. Energy harvesting is the process of capturing energy from one or more renewable energy sources and converting them into usable electrical energy. In this paper, we are providing the survey on energy harvesting systems for IoT devices. Firstly, we discussed why energy harvesting is required and different architectures of harvesting systems. Further, we presented the energy harvesting systems considering different energy sources and their comparisons. Overall, the paper summarizes the numerous energy harvesting systems for IoT devices that act as the background for the researchers working in this area.**

Keywords—Energy Harvesting; Energy sources; Internet of Things;

I. INTRODUCTION

Internet of Things (IoT) also acknowledged as the Internet of objects, is the networked interconnection of everyday objects. In IoT, things are the devices (physical or virtual) that are wirelessly connected through the internet like 4G enabled phones. Each of these devices has unique ID that identifies them uniquely. It is not only limited to connecting devices, it also allows devices to communicate (directly or indirectly) with each other by sending/receiving data. Devices should extract information by filtering, processing and condensing data and after that knowledge is inferred from that information that is used by devices for performing their respective operations. Some characteristics of the IoT systems are: Dynamic nature, Self-adapting, Self-configuring etc. Mostly, IoT devices are powered by the batteries. A major limitation of devices powered by battery is finite battery capacity because when IoT devices communicate with each other, large amount of energy is consumed due to which devices operate for limited duration only, as long as battery lasts. One of the solutions of this problem is to use replaceable batteries. This solution of replacing battery may be effective for small IoT system but for large IoT systems, this solution is not effective because of the cost of maintaining and replacing billions of batteries are very high. A promising solution to this problem is energy harvesting. Energy harvesting is the process of taking energy from one or more environmental (solar, wind, radio frequency, etc.) or other energy sources (body heat, finger strokes, foot strikes, etc.), accumulating them and converting them into usable electrical energy. This harvested electrical energy powers the IoT devices and increase the lifetime of the IoT system. The different energy harvester architectures [1] are (i) Harvest and Use: Just-in time energy is harvested and directly used (ii) Harvest-Store-Use: Whenever available, energy is harvested and stored which can be used in future at the time of requirement. In Harvest and Use architecture, the harvested energy directly powers the system. If harvested energy is not enough, the system will remain in idle state. In Harvest-Store-Use architecture, the harvested energy directly powers the system and is also stored for future use. When availability of harvested energy is larger than the present need of the system, then remaining energy is stored for later use. Alternatively, energy can also be stored until sufficient energy has been stored for system operation. The energy is stored in secondary storage which is used when primary storage (battery) is exhausted [2].

II. SOURCES FOR ENERGY HARVESTING

The energy harvesting sources are used to increase the lifetime and efficiency of the IoT system. The energy sources used for energy harvesting mechanism are either environmental sources like solar, wind, etc. or other energy sources like temperature difference, motion, footfall, breathing, etc. Table 1 shows the difference between various energy sources.

A. Solar and Wind Energy

Solar energy is the most efficient source of environmental energy, providing most of the energy with very high efficiency [3]. Sunlight is harvested by using solar or photo voltaic cells that are made of semiconductor material i.e. silicon. This technology directly converts sunlight into usable electricity. For the location where availability of light is guaranteed to be high, photo voltaic cell is the convenient solution. For indoor applications, specialized PV materials are used which are better suited for dim light. Large amount of energy lost when energy is transferred from harvester. To overcome this problem, maximum power point tracker (MPPT) circuit has been suggested which proficiently transferred harvested solar energy from harvester to rechargeable battery. The maintenance cost of solar cells is very low. Among all other sources, sunlight is considered as the most appropriate energy source for harvesting. It is estimated to provide 1.4 kW/m^2 [4].

978-1-5386-1959-9/17/$31.00 ©2017 IEEE

Theoretical efficiency of PV cell is 90% but practical efficiency of PV cell is 40% [5].

HydroWatch [26] is a single source solar energy harvesting system which uses TelosB [27] platform, two NiMH batteries and Maximum power point tracking (MPPT) for impedance matching. MPPT results in higher energy harvesting efficiency. The solar panel output is 276 mW at a voltage of 3.11 V. Battery is trickle charged in HydroWatch because it requires no software control and only simple circuit is required. Initially input regulator is required to limit the voltage of battery, but later it is found that it forced PV cell to operate at a point which is far from maximum power point. In HydroWatch, energy efficiency is increased by the removal of the input regulator but before its removal, it is estimated to have 50% efficiency. The drawback of using NiMH battery is the high self-discharge rate due to which lifetime of HydroWatch system is low. Another limitation of using NiMH battery is low input-output efficiency. The NiMH batteries are charged enough from sunlight within 30 minutes only to fulfill application requirements.

Heliomote [28] [36] [37] is another single source solar energy harvesting system which use Mica2 [29] [30] platform and two NiMH batteries but does not use MPPT. The solar panel outputs is 198 mW at a voltage of 3.3 V. Heliomote include overcharge and undercharge protection for rechargeable batteries. Undercharge protection is mandatory because it not only wastes the energy but can also cause damage to the battery. Overcharging protection is mandatory because overcharging of battery may lead to the instability of battery. Heliomote consider an energy management module which help device to learn about its energy need and energy availability. To realize the full benefit of energy harvesting, Heliomote make use of information provided by energy managing component to perform harvesting aware performance adaptation. An analysis shows that if rate of harvesting source power is greater in comparison to rate of depletion of power, then we can have perpetual operation. The efficiency of Heliomote is 80-84%.

Energy source	Characteristics	Harvester	Power Density	Advantages	Disadvantages
Solar energy	Ambient, Uncontrollable, Predictable	PV Panel	15 - 100 mW/cm2	Consistent; Available during daytime; high output voltage;	Not available in night; efficiency is low during cloudy days; Deployment Constraints
Wind energy	Ambient, Uncontrollable, Predictable	Anemometer	1200 mWh/day	Available in open areas	Not available in closed areas
Finger Motion	Active human power, fully controllable	Piezoelectric	2.1 mW	Available whenever needed	Energy is harvested only when finger is moved
Footfalls	Active human power, fully controllable	Piezoelectric	5 W	Available whenever needed	Highly variable output
Vibration (indoor Environments)	Ambient, Uncontrollable, Unpredictable	Electromagnetic Induction	0.2 *mW/cm*2	Without voltage source	Brittle materials
Thermal Energy	Ambient, Uncontrollable, Unpredictable	Thermocouple	≅50 mW/cm2	Long life, reliable with low maintenance	Low energy conversion efficiency
Motion	Non-Ambient, Controllable, Partly-predictable	Piezoelectric	200 μW/cm2	Light weight	Highly variable output
Breathing	Passive human power, uncontrollable, unpredictable	Ratchet-flywheel	0.42W	Available all the time.	
Radio frequency	Non-Ambient, Partly-controllable, Partly-predictable	Rectennas	1 μW/cm2	Sufficient in urban areas; very high energy density; Allow mobility	Few in suburbs; material in radioactive are extremely dangerous; low power density

TABLE I. COMPARISON BETWEEN VARIOUS ENERGY SOURCES [23] [24] [25]

Prometheus [35] is another single source solar energy harvesting system using the TelosB platform and its purpose is to hold the large amount of energy for longer period of time with minimum leakage current. Harvested energy is stored in two buffers, two super capacitor in series are used as primary buffer and secondary buffer is Lithium battery (have higher discharge efficiency than NiMH battery). To regulate the charging of the storage buffers, Prometheus uses software control. In this, firstly super capacitor is charged, and then if battery is charged below threshold and super capacitor is charged above the threshold then battery is charged until threshold is reached. If there is no harvested energy and super capacitor is charged below threshold then battery is used for powering the system until super capacitor is charged or battery falls below the threshold. Prometheus does not use the MPPT circuit for impedance matching.

Fleck [31] is another single source solar energy harvesting system which also considers two NiMH batteries because it does not require complex charging circuit and Integrated Fleck1 node but does not uses MPPT. The solar panel output is 2100 mWh/day. The system was designed to work in full solar light only not in dim sunlight. Analysis shows that powering the IoT device from battery by using regulator or DC-DC converter is beneficial as it allows the device to be powered for more time period and it powers the system at low voltage also like 1.2V. This is particularly useful when the device is battery-less, i.e., when super-capacitors are used in spite of batteries. A super capacitor keeps Fleck system alive for 14 hours and two super capacitor (in series) keep Fleck system alive for 27 hours.

Everlast [32] is another solar energy harvested node but with super capacitor. It does not include battery but harvesting efficiency is high as compared to Heliomote and Prometheus. Key points which are taken in consideration at the time of system design is, Super capacitor is used for increasing number of charge and discharge cycle and output of solar cell is constantly optimized by MPPT. Ever last is the integrated system which consists of energy harvesting sub-system along with micro-controller, sensors and radio. It make use of PFM (Pulse Frequency Modulated) regulator for super capacitor charging. To efficiently charge the same, switched-capacitor circuit and buck converter are used. The PFM controller shuts down the regulator when the super-capacitor is fully charged by sending the "Shutdown" signal. Everlast claims a lifespan of 20 years with 50% duty cycle. Analysis shows that efficiency varies depending upon operating voltage and super capacitor size.

Solar Biscuit [33] is another single source solar energy harvesting system similar to the Everlast and uses super capacitor and integrated node but does not uses MPPT circuit. In this super capacitor is connected to the solar cell directly. Solar-Biscuit has no input and output voltage regulator for super capacitor.

Sun Flower [34] is another solar energy harvesting system which uses super capacitor but does not use MPPT circuit for impedance matching. It uses 4 PIN photo diodes instead of solar panel. Similar to Everlast, Sun Flower includes a switching regulator for charging the super capacitor by using photo diodes. Analysis shows that Maximum lifetime of system is unlimited.

Ref. [42] describe a method to harvest wind energy with the help of anemometer based solution. Here the motion of an anemometer shaft is used for harvesting the energy. A pulsed buck-boost converter is used for converting the harvested energy to battery potential. In this method, battery is trickle charged. Analysis shows that the energy harvesting capability is in range of ten to hundreds of microwatts up to approximately one mill watt. If this solution is used by any sensor device, then it will increase the lifetime of that sensor device.

AmbiMax [38] is a multi-source energy harvesting system which uses super capacitor as energy storage. Like Prometheus, AmbiMax has a primary and secondary storage. Unlike Prometheus, Hardware controls the super capacitor charging. All the above explained system uses solar energy for harvesting but does not consider the time when solar energy is not available. To overcome this problem AmbiMax uses solar and wind energy. Each harvesting sub-system has its own super-capacitor corresponding to each of the energy source. AmbiMax firstly solve MPPT or Impedance matching problem between the supply and source and then charge super capacitor at maximum efficiency. In AmbiMax, switching regulator is positioned in between the source and capacitor for blocking the reverse flow of current from super capacitor and improving the harvesting efficiency which results in efficient charging of super capacitor. Analysis shows that super capacitor is charged 12.5 times faster and 3 times more energy is harvested.

B. Thermal Energy

Thermal energy is the energy that comes from heat. Thermal energy is also related to variations in temperature. The techniques used for thermal energy harvesting are thermoelectric and pyro electric. Thermoelectric technique directly converts temperature difference into usable energy form by using See beck effect. The harvesting efficiency of thermoelectric is around 5-8 %. The thermoelectric devices are used in space and terrestrial applications. Several papers discussed how thermoelectric harvest the energy [6][7][8]. Pyro electric technique generates electrical energy when there is change in temperature. Pyro electric technique uses pyro electric crystal that generates electricity when heated or cooled. Pyro electricity technique should not be confused with thermoelectric technique because pyro electricity results in temporary voltage across the crystal and thermoelectric results in permanent voltage across the crystal. There is always temperature difference between environment temperature and human body temperature and this temperature difference is a good source of thermal energy. Thermal energy is difficult to convert to usable electrical energy.

Ref. [41] describes a method to harvest the natural temperature difference between soil and air to generate electrical energy by using thermoelectric generator. Analysis shows that power conversion efficiency of best thermoelectric generator available is very low for the above explained method. The power output generated by this method depends upon type of soil and water content.

C. Mechanical Energy

Mechanical energy is the energy that is possessed by an object either by its position or by its motion. Mechanical energy is divided into two types, i.e., kinetic energy and potential energy. Kinetic energy is related to motion of an object and potential energy is related to position of an object or work done by an object. The sources of kinetic energy are motion, vibration, pressure and human activity. The techniques that are used for harvesting mechanical energy are piezoelectric, electrostatic and electromagnetic. In piezoelectric, piezoelectric material directly converts kinetic energy into usable energy. This material is used by various researchers to develop new piezoelectric harvester [[9][10][11]. In electrostatic, harvesting is based on the changing capacitance of vibration-dependent varactors. Authors in.[12] well explained the basic working principle of electrostatic and piezoelectric. The various electrostatic harvested are discussed in various papers [13][14][15]. In electromagnetic, energy is harvested by using the principle of electromagnetic induction. Various researchers contributed in identifying the techniques that generate power from electromagnetic resources [16][17][18]. The Electrostatic and Piezoelectric harvester's output voltage ranging from 2 to 10V, and the electromagnetic harvester output maximum voltage of 0.1V [19].

Ref. [40] harvest the kinetic (motion) energy and describe the method for predicting energy harvested from acceleration traces. To characterize the energy availability associated with 7 human motions like walking, relaxing, fast walking, running, going upstairs, going downstairs and cycling, they analyze motion dataset over 40 participants. The sensing unit is placed in shirt pocket, waist belt and trouser pocket for 7 human motions. Analysis shows that amount of energy harvested vary from person to person and different amount of energy is harvested from different human activity. Also, amount of energy harvested depends upon height and weight of the person.

D. Radiant Energy

Radiant energy is in the form of radio frequencies that are emitted from television, base station, microwave, oven, smartphones, and network router. In electromagnetic technique, this radio frequency signals are harvested with the help of large aperture power receiving antennae by converting these attained waves into utilizable DC power. Their performance is dependent on RF to DC conversion efficiency and the amount of power received by antenna. RF signals are used by various researchers for energy harvesting [20] [21]. Theoretical efficiency of solar panel is 100% but practical efficiency of solar panel is 85 % [22].

Further, Ref. [39] discussed a wireless RF energy harvesting system usually consist of antenna, transceiver, a wireless energy harvesting (WEH) component and a power management unit (PMU). WEH harvests the RF energy and PMU controls the energy management in each unit and charge battery with the help of available harvested energy. Two switches are used, one is between storage element and battery and second is between battery and sensing unit. Harvested energy is stored in storage element. If energy in battery device goes below threshold, then PMU sends recharge command to storage element. When energy level of device is 1.1 times of the minimum power (P_{min}) then device goes out of service until it recharge itself again to more than 1.5 P_{min} .

III. CONCLUSION

This paper presents literature review of various energy harvesting systems for IoT devices. Harvesting energy from the environmental sources and other energy sources is considered as a promising solution for increasing the lifetime and efficiency of the IoT systems. There are number of limitations in energy harvesting systems like: low amount of harvested energy, unavailability of energy source, inefficiency of harvested system etc. Thus, numerous research efforts has been done in the past to overcome these limitations and new harvesting models are generated. In this paper, we are providing the survey of energy harvesting systems and their comparisons that could help the researchers working in the area of energy harvesting. Today, energy harvesters are widely used in various application domains like industry, medical, agriculture etc. and it is very important area that needs to be explored further.

References

[1] Kansal, A., Hsu, J., Zahedi, S., & Srivastava, M. B. (2007). Power management in energy harvesting sensor networks. *ACM Transactions on Embedded Computing Systems (TECS)*, *6*(4), 32.

[2] Jiang, X., Polastre, J., & Culler, D. (2005, April). Perpetual environmentally powered sensor networks. In *Proceedings of the 4th international symposium on Information processing in sensor networks* (p. 65). IEEE Press.

[3] King, R. R., Law, D. C., Edmondson, K. M., Fetzer, C. M., Kinsey, G. S., Yoon, H., ... & Karam, N. H. (2007). 40% efficient metamorphic GaInP/ GaInAs/ Ge multijunction solar cells. *Applied physics letters*, *90*(18), 183516.

[4] Sudevalayam, S., & Kulkarni, P. (2011). Energy harvesting sensor nodes: Survey and implications. *IEEE Communications Surveys & Tutorials*, *13*(3), 443-461.

[5] Atallah, R., Khabbaz, M., & Assi, C. (2016). Energy harvesting in vehicular networks: a contemporary survey. *IEEE Wireless Communications*, *23*(2), 70-77.

[6] Lawrence, E. E., & Snyder, G. J. (2002, August). A study of heat sink performance in air and soil for use in a thermoelectric energy harvesting device. In *Thermoelectrics, 2002. Proceedings ICT'02. Twenty-First International Conference on* (pp. 446-449). IEEE.

[7] Sodano, H. A., Dereux, R., Simmers, G. E., & Inman, D. J. (2004, October). Power harvesting using thermal gradients for recharging batteries. In *Proceedings of 15th international conference on adaptive structures and technologies* (pp. 25-27).

[8] Sodano H A, Inman D J, and Park G., "A Review of Power Harvesting from Vibration Using Piezoelectric Materials," The Shock and Vibration Digest, 2004, v 36, pp. 197–205. Sodano, H. A., Inman, D. J., & Park, G. (2004). A review of power harvesting from vibration using piezoelectric materials. *Shock and Vibration Digest*, *36*(3), 197-206.

[9] Amirtharajah, R., & Chandrakasan, A. P. (1998). Self-powered signal processing using vibration-based power generation. *IEEE journal of solid-state circuits*, *33*(5), 687-695..

[10] Cavallier, B., Berthelot, P., Nouira, H., Foltete, E., Hirsinger, L., & Ballandras, S. (2005, September). Energy harvesting using vibrating structures excited by shock. In *IEEE Ultrasonics Symposium* (Vol. 2, pp. 943-945).

[11] Cornwell, P. J., Goethal, J., Kowko, J., & Damianakis, M. (2005). Enhancing power harvesting using a tuned auxiliary structure. *Journal of Intelligent Material Systems and Structures*, *16*(10), 825-834.

[12] Beeby, S. P., Tudor, M. J., & White, N. M. (2006). Energy harvesting vibration sources for microsystems applications. *Measurement science and technology*, *17*(12), R175.

[13] Tashiro, R., Kabei, N., Katayama, K., Tsuboi, E., & Tsuchiya, K. (2002). Development of an electrostatic generator for a cardiac pacemaker that harnesses the ventricular wall motion. *Journal of Artificial Organs*, *5*(4), 0239-0245.

[14] Meninger, S., Mur-Miranda, J. O., Amirtharajah, R., Chandrakasan, A., & Lang, J. H. (2001). Vibration-to-electric energy conversion. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, *9*(1), 64-76.

[15] Miyazaki, M., Tanaka, H., Ono, G., Nagano, T., Ohkubo, N., Kawahara, T., & Yano, K. (2003, August). Electric-energy generation using variable-capacitive resonator for power-free LSI: efficiency analysis and fundamental experiment. In *Low Power Electronics and Design, 2003. ISLPED'03. Proceedings of the 2003 International Symposium on* (pp. 193-198). IEEE.

[16] Beeby, S. P., Tudor, M. J., Koukharenko, E., White, N. M., O'Donnell, T., Saha, C., ... & Roy, S. (2004). Micromachined silicon generator for harvesting power from vibrations.

[17] Huang W S, Tzeng K E, Cheng M C and Huang R S, "Design and fabrication of a vibrational micro-generator for wearable MEMS," Proceedings of Eurosensors XVII, Guimaraes, Portugal, 2003, pp 695–697.

[18] Kulah, H., & Najafi, K. (2004). An electromagnetic micro power generator for low-frequency environmental vibrations. In *Micro Electro Mechanical Systems, 2004. 17th IEEE International Conference on.(MEMS)* (pp. 237-240). IEEE.

[19] Roundy, S. J. (2003). *Energy scavenging for wireless sensor nodes with a focus on vibration to electricity conversion* (Doctoral dissertation, University of California, Berkeley).

[20] Aminov, P., & Agrawal, J. P. (2014, May). RF energy harvesting. In *Electronic Components and Technology Conference (ECTC), 2014 IEEE 64th* (pp. 1838-1841). IEEE.

[21] Kamalinejad, P., Mahapatra, C., Sheng, Z., Mirabbasi, S., Leung, V. C., & Guan, Y. L. (2015). Wireless energy harvesting for the internet of things. IEEE Communications Magazine, 53(6), 102-108.

[22] Atallah, R., Khabbaz, M., & Assi, C. (2016). Energy harvesting in vehicular networks: a contemporary survey. *IEEE Wireless Communications*, *23*(2), 70-77.

[23] Cetinkaya, O., & Akan, O. B. (2017). Electric-Field Energy Harvesting in Wireless Networks. *IEEE Wireless Communications*, *24*(2), 34-41.

[24] Sudevalayam, S., & Kulkarni, P. (2011). Energy harvesting sensor nodes: Survey and implications. *IEEE Communications Surveys & Tutorials*, *13*(3), 443-461.

[25] Kulah, H., & Najafi, K. (2008). Energy scavenging from low-frequency vibrations by using frequency up-conversion for wireless sensor applications. *IEEE Sensors Journal*, *8*(3), 261-268.

[26] Taneja, J., Jeong, J., & Culler, D. (2008, April). Design, modeling, and capacity planning for micro-solar power sensor networks. In *Proceedings of the 7th international conference on Information processing in sensor networks* (pp. 407-418). IEEE Computer Society.

[27] Polastre, J., Szewczyk, R., & Culler, D. (2005, April). Telos: enabling ultra-low power wireless research. In *Proceedings of the 4th international symposium on Information processing in sensor networks* (p. 48). IEEE Press.

[28] Lin, K., Yu, J., Hsu, J., Zahedi, S., Lee, D., Friedman, J., ... & Srivastava, M. (2005, November). Heliomote: enabling long-lived sensor networks through solar energy harvesting. In *Proceedings of the 3rd international conference on Embedded networked sensor systems* (pp. 309-309). ACM.

[29] Hill, J. L., & Culler, D. E. (2002). Mica: A wireless platform for deeply embedded networks. *IEEE micro*, *22*(6), 12-24.

[30] "Mica, Mica2, Mica2Dot, MicaZ, Telos," http://www.xbow.com/products.

[31] Corke, P., Valencia, P., Sikka, P., Wark, T., & Overs, L. (2007, June). Long-duration solar-powered wireless sensor networks. In *Proceedings of the 4th workshop on Embedded networked sensors* (pp. 33-37). ACM.

[32] Simjee, F., & Chou, P. H. (2006, October). Everlast: long-life, supercapacitor-operated wireless sensor node. In *Low Power Electronics and Design, 2006. ISLPED'06. Proceedings of the 2006 International Symposium on* (pp. 197-202). IEEE.

[33] Minami, M., Morito, T., Morikawa, H., & Aoyama, T. (2005, June). Solar biscuit: A battery-less wireless sensor network system for environmental monitoring applications. In *The 2nd international workshop on networked sensing systems*.

[34] Stanley-Marbell, P., & Marculescu, D. (2007, January). Sunflower: Full-system, embedded microarchitecture evaluation. In *International Conference on High-Performance Embedded Architectures and Compilers* (pp. 168-182). Springer, Berlin, Heidelberg.

[35] Jiang, X., Polastre, J., & Culler, D. (2005, April). Perpetual environmentally powered sensor networks. In *Proceedings of the 4th international symposium on Information processing in sensor networks* (p. 65). IEEE Press.

[36] Kansal, A., Hsu, J., Zahedi, S., & Srivastava, M. B. (2007). Power management in energy harvesting sensor networks. *ACM Transactions on Embedded Computing Systems (TECS)*, *6*(4), 32.

[37] Raghunathan, V., Kansal, A., Hsu, J., Friedman, J., & Srivastava, M. (2005, April). Design considerations for solar energy harvesting wireless embedded systems. In *Proceedings of the 4th international symposium on Information processing in sensor networks* (p. 64). IEEE Press.

[38] Park, C., & Chou, P. H. (2006, September). Ambimax: Autonomous energy harvesting platform for multi-supply wireless sensor nodes. In *Sensor and Ad Hoc Communications and Networks, 2006. SECON'06. 2006 3rd Annual IEEE Communications Society on* (Vol. 1, pp. 168-177). IEEE.

[39] Kamalinejad, P., Mahapatra, C., Sheng, Z., Mirabbasi, S., Leung, V. C., & Guan, Y. L. (2015). Wireless energy harvesting for the internet of things. *IEEE Communications Magazine*, *53*(6), 102-108.

[40] Gorlatova, M., Sarik, J., Grebla, G., Cong, M., Kymissis, I., & Zussman, G. (2015). Movers and shakers: Kinetic energy harvesting for the internet of things. *IEEE Journal on Selected Areas in Communications*, *33*(8), 1624-1639.

[41] Lawrence, E. E., & Snyder, G. J. (2002, August). A study of heat sink performance in air and soil for use in a thermoelectric energy harvesting device. In *Thermoelectrics, 2002. Proceedings ICT'02. Twenty-First International Conference on* (pp. 446-449). IEEE.

[42] Weimer, M. A., Paing, T. S., & Zane, R. A. (2006). Remote area wind energy harvesting for low-power autonomous sensors. *system*, *2*(1), 2.