

Energy Harvesting in wireless communication: A survey

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Abstract. Wireless Sensor Network is an emerging technology that has the potential to be used in futuristic applications. Sensor nodes are energy-constrained. They rely on batteries with limited capacity which impact their lifetime or mobility. To address this problem, energy harvesting technology is a solution that aims to avoid the premature energy depletion of nodes. It recharges their batteries using an energy harvesting system from the environment. In this review work, we present the concept of energy harvesting technology (EH) and Energy-Harvesting for Wireless Sensor Network (EH-WSN). We then discuss many schemes in the literature to save energy consumption of the energy harvesting sensor networks. We study their protocol design strategies and working principals. We also summarize their merits, demerits along with some future research directions.

1 Introduction

In the last few decades, wireless communications have known a phenomenal progress. They have brought extraordinary convenience in our everyday lives. A wireless data transmission does not need wires or cables. However, conventional wireless systems are limited by the batteries used to power wireless nodes. This have an impact on their mobility or their lifetime and thus prevent them from being deployed in increasingly widespread applications.

Green communication (GC) has attracted a lot of attention recently. It has been proposed as an innovative strategy to reduce greenhouse emissions by promoting harvesting solar energy, wind energy, and the exploitation of other renewable resources. On the other hand, wireless power transfer (WPT) has emerged as a hot topic allowing the transmission of electrical power without wires or contacts.

Given these recent developments, it becomes essential to adopt wireless power transfer or energy harvesting (EH) to take full advantage of the potential of wireless communication [1].

The energy harvesting (EH) technology tries to maintain wireless sensor nodes over prolonged deployment periods. Energy-Harvesting Wireless Sensor Network (EH-WSN) refers to harvesting environmental energy, such as solar, Radio Frequency (RF) and wind energy, converting it to electrical energy and then storing it in a storage device. The harvested energy powers the sensor nodes. If the harvested energy source is abundant, then a sensor node can be powered continuously.

The paper is a comprehensive survey on energy harvesting techniques in the field of EH-WSNs. It provides also the basic concepts of EH and the motivation behind using energy harvesting systems in wireless sensor nodes. The survey summarizes recent studies for saving energy in EH-WSNs with a focus on their working principles and an outline of their advantages, shortcomings for possible improvement.

This paper is organized as follow: In section 2, we start by exploring the concept of energy harvesting. We present harvesters' applications, characteristics and types of energy harvesting sources. In section 3, we took a close look at Energy-Harvesting Wireless Sensor Network. We explain why energy harvesting is crucial in WSNs and we present classes of energy harvesting sources for WSNs. Section 4 discusses different energy management schemes in EH-WSN. We summarize their design strategies /working principles and also highlight their merits and their demerits.

2 Energy Harvesting (EH)

Energy harvesting (or energy scavenging) is a technique used to address the problem of limited node lifetime. It refers to the process of scavenging and converting ambient energy into electrical energy to power autonomous electronic devices or circuits [2]. Energy harvesting materials and systems have emerged as a significant field of research and continues rapid expansion. Harvesters are used for large number of applications (see figure 1).

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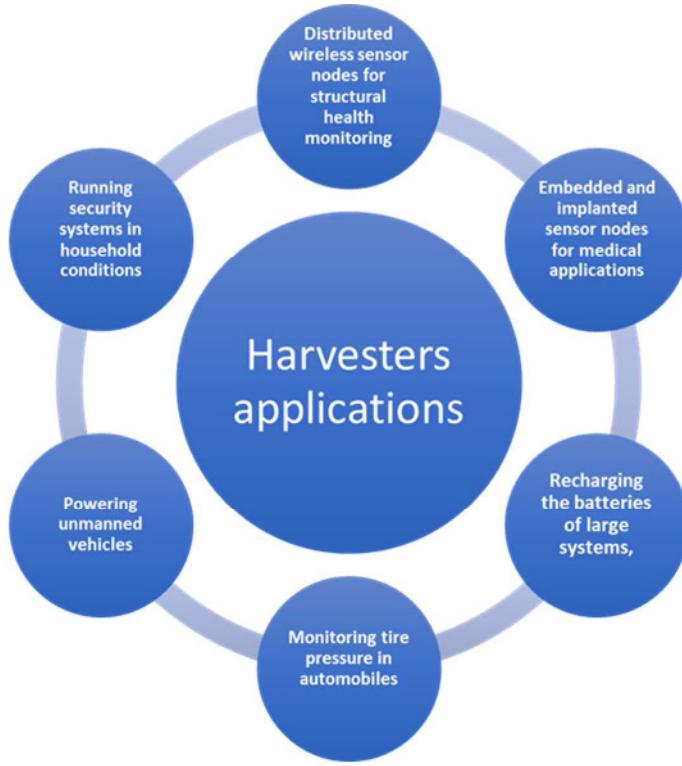


Fig. 1. Harvesters applications

2.1 Energy harvesting sources:

There are many types of energy sources to harvest energy from in wireless communications. Based on controllability and predictability properties [3], they can be classified into four categories. An energy harvesting system is said to be controllable if it can control fully/partially its energy harvesting sources or not. Predictability refers to the study of the extent to which the energy harvesting source can be predicted [4].

- Uncontrollable and unpredictable: Those energy sources cannot be controlled to produce energy at specific times and behave in totally unpredicted ways. Mechanical vibration is an example of such energy source. Mechanical energy harvesting using piezoelectric and electromagnetic harvesters convert vibration into electricity; however, it is difficult to predict when or where the vibration will occur, and it is even more difficult to intentionally generate it [1].
- Uncontrollable but predictable: Those energy sources cannot be controlled to produce energy at specific times in specific location. The generated energy exhibits a behavior that follows predictable patterns within some error margin. For instance, solar energy cannot be controlled. It is hard to control the movement of the sun or the weather in order to obtain the desired level of solar energy, but solar energy depends on diurnal and seasonal cycles that can be modelled to predict availability [3].
- Fully controllable: Energy can be produced when desired. A powered flashlight can generate some

energy by the user when shaken wherever and whenever needed.

- Partially controllable: System designers or users may influence the energy generation but the resulting behavior lacks full determinism.

2.2 Energy harvesting types:

The energy harvesting system can be categorized based on the nature of energy harvested as follow [5, 6] :

- Mechanical energy: is converted from vibration, motion, stress, pressure or strain into electricity.
- Wind energy: is generated from wind or air.
- Solar/ Light: The photons from the light source are converted into electricity using photovoltaic cells. When the photons arrive from the light source, the photovoltaic cell will release electrons to produce electricity.
- Electromagnetic energy: is produced from ambient environment (radiations from cellular base station, TV transmitter or WIFI router) or from dedicated power transmitter.
- Human body energy produced by body parts movement, body temperature.
- Hydropower energy is generated from flowing water and tides.
- Geothermal energy originated from the internal heat of the earth.
- Biomass energy: from biodegradable wastage, human urine, chemical, and biological sources.

Table 1 tabulates the working principal of different energy sources. It also lists for each energy the typical amount of energy produced and its characteristics.

Table 1 Comparison between energy harvesting sources based on [7, 8]

Energy source	Working principal	Typical amount of energy	Characteristics
Solar	Photovoltaic	15mW/cm ² 100mW/cm ² (sunny)	Ambient, uncontrollable, predictable
Wind	Turbine	1200Wh/day	Ambient, uncontrollable, predictable
Radio frequency	Rectenna	0.001 μW/cm ² (WiFi 2.4 Ghz) 0.1 μW/cm ² (GSM 900 Mhz)	Non-Ambient, Partially controllable, Partially-predictable
EM Waves	Coils	125 μW/cm ³ –2.65 Hz	Ambient, uncontrollable, Predictable
Vibration (indoor Environments)	Microgenerator	3μW/cm ³ (human motion) 800 μW/cm ³ (machines)	Ambient, Uncontrollable, Unpredictable
Breathing	Ratchet–flywheel	0.42W	Passive human power, uncontrollable, unpredictable
Footfalls	Piezoelectric	5W	Active human power, fully controllable

3 Energy-Harvesting Wireless Sensor Network (EH-WSN)

3.1 Motivation for Energy harvesting wireless communications:

Wireless Sensor Networks (WSNs) have attracted much attention in recent years. They have become pervasive and are being deployed in many applications like internet of things, cyber physical systems and other evolving areas. For applications where the system is expected to operate for extended durations, energy becomes a major bottleneck.

Network lifetime and energy performance have become the key characteristics for evaluating energy efficiency in Wireless Communications. Several techniques have recently been proposed focusing on minimizing energy consumption and improving the network lifetime [9, 10].

WSN nodes are placed in remote, hard to reach places, where it is not practical to recharge or replace depleted batteries. When a node is dead, it will fade out and disengage from the network unless either the source of energy is replenished or some harvesting mechanism is introduced to fill the energy gap [11]. Even when not in use, current leakages can drain batteries out; additionally, any packaging defects due to long-term wear and tear might cause environmental issues [12].

Depending on the application requirements, the sensor node lifetime might range from months to years. The sensor node operates in active, idle and sleep modes. Even inactive, when it is on sleep, a considerable amount of power is wasted as shown in Table 2.

Sensor network lifetime depends on the number of active nodes and network connectivity. Data processing, sensing and communication frequency of the node greatly impact the lifetime of its battery. So, harvesting and energy conservation techniques must be used to

minimize energy consumption and maximize the network lifetime.

Several articles have tackled the problem of lifetime extension in battery-powered sensor nodes. Some of them are energy-efficient MAC protocols : SMAC [13] and BMAC [14]. Others are energy efficient protocols for routing and data dissemination [15, 16]. Duty-cycling strategies were also proposed [17].All those techniques optimize the energy consumption of the sensor node to maximize its lifetime. Nevertheless, the lifetime remains bounded and finite. The above techniques help extending the application lifetime and/or the time interval between battery replacements, but do not overcome inhibitions related to energy.

Obviously, we cannot optimize all the performance metrics of a WSN simultaneously. A higher battery capacity will increase its cost, weight & size. A low duty-cycle means decreased sensing reliability. A higher transmission range needs more power, and lower transmission range uses routing paths with multiple hops implying more power consumption at each hop [18].

Energy Harvesting is being actively pursued to address the problem of limited node lifetime. It is a promising technique and one of the most recent advances in communications systems. Any communication system that harvests energy from the ambient environment or a dedicated power transmitter in a cable-free or battery-free manner is referred to as energy harvesting wireless communication [1].

Table 2 Energy consumption of widely used commercial sensor motes.

Sensor mote	Operating voltage	Sleep	Processing	Receive	Transmit	Idle	Expected lifetime
IRIS [19]	2.7 V-3.3 V	8 μ A	8 mA	16 mA	15 mA	-	216 hrs [20]
MICAz [21]	2.7 V	15 μ A	8 mA	19.7 mA	17.4 mA	-	187 hrs [20]
TELOS B [22]	1.8V- 3.6 V	5.1 μ A	1.8 mA	19.7 mA	17.4 mA	-	241 hrs[20]
SunSpot [23]	5V ($\pm 10\%$)	33 μ A	104 mA	40 mA	40 mA	24 mA	-

Providing wireless devices with energy harvesting capability allows them to continuously obtain energy from the environmental sources either by natural or man-made phenomena. This offers many promising advantages for wireless networking : energy self-sustainability, virtually perpetual operation, reduction of conventional energy use and the consequent carbon footprint, no-battery replacement and/or no tethering to electricity grids providing untethered mobility, and the ability to deploy these devices at hard-to-reach locations within concrete buildings, remote rural areas, and within the human body [24].

A sensor node with the energy harvesting capability can be powered almost indefinitely if the harvested energy source is large and available on a periodic or continuous basis. Since a WSN node is energy-constrained until the next harvesting opportunity (recharge cycle), it can optimize its energy usage to maximize its performance during that interval. To improve its sensing reliability, a node can increase its sampling frequency or duty-cycle, or increase its transmission power to shorten the length of routing paths. The energy harvesting strategies are able to handle the trade-off between performance parameters and lifetime of sensor nodes discussed earlier. Estimating the magnitude and periodicity of the harvestable source and dynamically deciding which parameters to tune while avoiding energy exhaustion before the next recharge cycle. The estimate of the periodicity and the magnitude of the harvestable source and the decision of which parameters to tune while

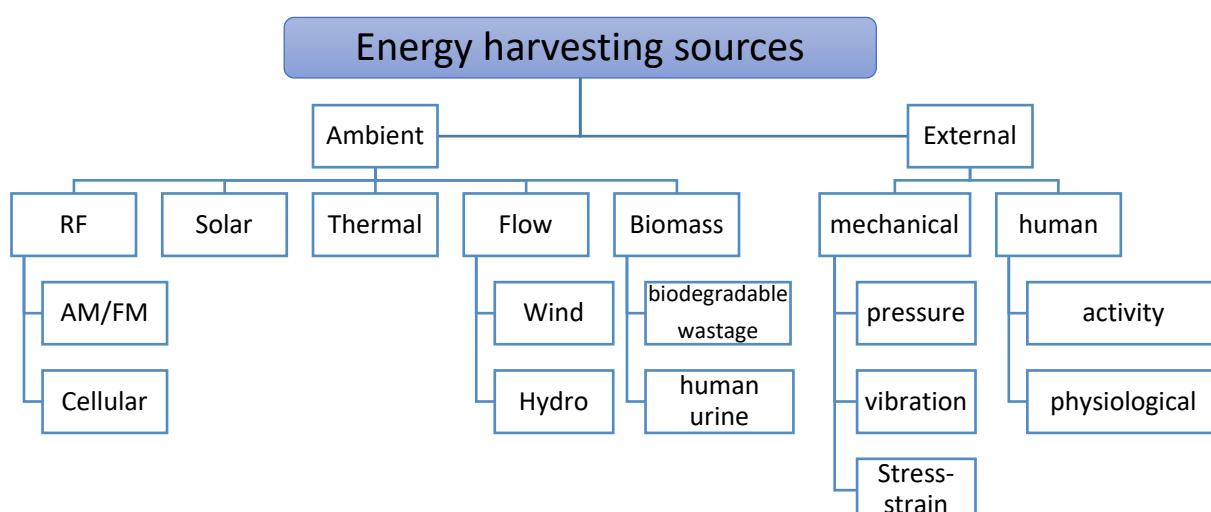
avoiding premature battery depletion before the next recharge cycle, are a major challenge [7].

3.2 Energy harvesting sources in WSN

Basically, Energy harvesting sources for WSN are classified as ambient and external [25]. Ambient sources are collected from the surrounding environment: RF-based energy (Radio Frequency), solar energy, flow-based energy, and thermal energy. External refers to sources that are explicitly deployed for energy harvesting purposes.

Figure 2 shows examples of ambient/external sources for WSN and their subdivision into more categories. Due to the size, mobility, or power constraints of wireless nodes, not all energy sources can be employed in all wireless communications systems. Hence, choosing the appropriate source for harvesting in the design of energy harvesting wireless communication systems is critical. Figure 3 shows common energy sources used in energy harvesting wireless communications.

Solar energy is the most readily available source of energy. It is not controllable but due to diurnal and seasonal cycles, it is predictable. The small size of solar panels is suitable for wireless sensor nodes making it among the most promising harvestable energy sources [3].

**Fig 2 :** Taxonomy of energy harvesting sources in WSNs

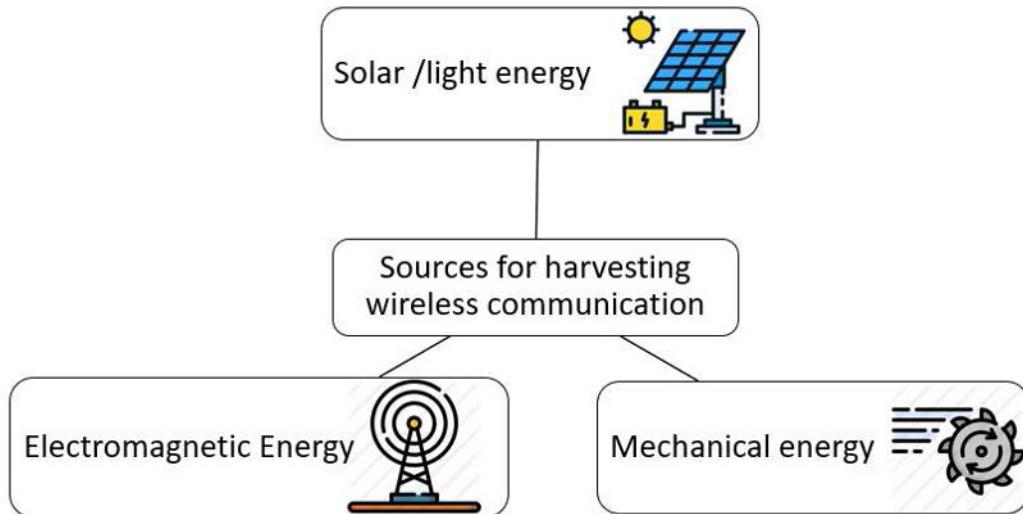


Fig 3 : Some commonly used energy sources for EH wireless communications

4 Energy management schemes in WSN

In this section, we discuss different schemes used to save energy consumption in energy harvesting sensor networks. They are divided into four categories based on [26]: Clustering and routing, energy balancing, coverage-awareness, and node placements.

4.1 Clustering and routing based schemes

Clustering is the task of dividing the network into a number of clusters. Each cluster is composed of a cluster head (CH) and multiple cluster members. The main issue of the clustering protocol is the selection of CH. It can be selected based on the energy status of the nodes or can be the one that will minimize the communication range R_c of the cluster member.

Routing is the process of finding out an optimal path between the source node to the destination node, that is, between two sensor nodes or between sensor node and the sink. The design of energy-efficient routing protocol is very challenging because it consumes more energy. The objective of energy harvesting WSN based routing protocol is to extend network lifetime and increase throughput [27].

The authors in [28] designed an opportunistic routing protocol called EHOR (Energy Harvesting Opportunistic Routing). It is powered solely by ambient energy harvesters (WSN-HEAP) with no batteries. A node chooses the best forwarding candidates in its neighborhood depending on their distance from the sink and on their residual energy. Those potential forwarders are partitioned in regions. The one closest to the sink rebroadcasts a packet after receiving it. EHOR has maximized goodput and efficiency of the network.

Energy Harvesting aware clustering with Fuzzy Petri (EHFP) was proposed in [29]. It selects the cluster heads considering the harvested energy, concentration and the centrality of each node. It works in the three-level of hierarchy and also introduces the concept of multiple

backup for each CH. This increases the robustness of the network and avoids multiple re-clustering when the CH died.

Bozorgi et al . [30] proposed a novel hybrid algorithm that works in both static and dynamic clustering environments called NEEC (Novel Energy Efficient Clustering). It is a multi-hop routing protocol that uses a distributed-centralized approach and considers parameters, such as the energy level, the amount of harvested energy and the number of neighbors in the clustering process. NEEC algorithm has improved the network stability and efficiency and increased the number of packets received at the base station.

Authors in [31] designed unequal-sized clustering algorithm called (CREST). It is a distributed and it works in two-tier routing-based topology. It divided the network into virtual tracks of unequal size. The CH elected is the one with the highest node degree defined from an energy point of view.

4.2 Energy balancing based schemes

It is a critical issue in WSN. It aims avoiding early depletion of nodes by efficiently managing their traffic load. In fact, imbalanced energy consumption causes a variation in the lifetime of sensor nodes. Many mechanisms have been used for energy balancing in WSN, such as dynamic routing, duty cycling, scheduling technique, time synchronization and minimization of delay [26, 32].

In [33], authors addressed the problem of scheduling weighted packets with deadlines in an energy-harvesting sensor node. They have proposed an optimal offline framework and deterministic online algorithms to achieve a maximized weighted throughput, that is the total value of the sent packets. Every packet is subject to energy harvesting and deadline constraints.

In [34], authors have discussed a constrained formulation using MDP (Markov Decision Process) to minimize the distortion in data compression while balancing energy. The algorithm tries to control lossy data compression over fading channels. To keep prior

knowledge of the sensor network, the second algorithm proposed is based on Lagrangian relaxation approach used to update current information.

4.3 Coverage awareness schemes

In addition to location calculation, tracking, and deployment, coverage is considered one of the fundamental issues that affects networks performance in WSN. Sensor coverage awareness measures the sensing capability of the nodes and builds a geometric relationship between some target points and sensor nodes [26]. It is a measure of quality of service of a sensor network by defining how well sensors can monitor a given area [35].

In [36], authors proposed a distributed algorithm ensuring coverage in energy harvesting in WSNs. The proposed protocol, called MEP (Maximum Energy Protection), addressed the DMLC-EH problem (Distributed Maximum Lifetime Coverage with Energy Harvesting). The main idea is to alternatively activate sensors to form a minimal set to cover all targets such as the network lifetime is maximized.

The authors in [37] presented a robust coverage area for energy harvesting wireless sensor networks. All the sensor nodes are equipped with solar panels and deployed in some specific sensing area to cover the target points. The solution computes the sleep and wake time of the sensor nodes to ensure that all the targets are monitored by at least one sensor node with a certain probability ($1-\epsilon$). where, ϵ is a probability of the coverage failure or energy outage.

4.4 Node placement schemes

The objective of node placement is to maintain a proper connectivity among the sensor nodes in the network. Implementing node placement schemes will help to construct an effective deployment between the sensor node to the base station. It is a very challenging problem since it is proven to be NP-Hard for most of the formulations of sensor deployment [38].

In [39], authors have addressed the constrained relay node placement problem based on Energy Harvesting WSNs (EH-CRNP) for connectivity or survivability requirements . They proposed a mixed-integer linear program (MILP) approximation that places relay nodes

at locations where they can harvest large amount of energy. The locations are chosen such that the energy harvesting potential is high. Each sensor node will be assigned a weight value that is related to its energy harvesting potential.

Authors in [40] have formulated the SMRMC (sustainable minimum-relay maximum-connectivity deployment) problem as multi-constraint and mixed-integer linear program (MILP) , which is proved to be NP-hard. The proposed MILP minimizes the number of relay nodes to be deployed in the network. The constraints considered are connectivity, sustainability, unpredictable energy harvesting and depletion rates.

Summary:

In this section, we have presented many energy management techniques for EH-WSN. We have summarized their design strategies and working principles. We also highlighted their merits and their shortcomings. The detailed summary is provided in tabular form as described in Table 3.

In clustering-routing based schemes [28-31], even if they are meant for EH-WSN, the selection of the cluster head is based on residual energy of the node with no consideration of the predicted energy harvesting of the node. The question is: Will those schemes still ensure the energy harvesting capability when the energy harvesting system is uncontrollable and difficult to predict?

The presented energy balancing schemes [33, 34] have tried to improve the performance of the network but they are not energy harvesting aware. The constructed routes enhance the network performance by balancing energy among the sensor nodes. Nevertheless, the prediction of harvested energy is not considered in constructing those routes.

Coverage based algorithms [36, 37] have been proposed to achieve coverage lifetime but they don't provide a coordination with the energy harvesting system.

The node placement techniques [39, 40] achieved an effective node placement but they also lack coordination with the energy harvesting system.

Table 3 Summery of energy management schemes in EH-WSN

Algorithms	Authors, year	Merits	Shortcomings/ Future research directions
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EHOR	Eu et al. [28], 2010	Reduced delay and improved goodput	*) The network topology is assumed to be linear (nodes are uniformly deployed over a given interval). **) 2D topologies are not supported.
EHFP	Mostafa et al. [29], 2014	Maximized lifetime network and robustness of cluster head	Further improvement for selecting the cluster head can be obtained by using type-2 fuzzy petri nets and TOPSIS approach.
NEEC	Bozorgi et al. [30], 2017	Improved network stability and efficiency	Extra overhead processing due to: *) Computation of distance to the sink by all the nodes based on the received signal strength. **) Transmitting of location messages by nodes to the sink.
CREST	Afsrar et al. [31], 2019	Improved throughput and energy efficiency	Integrating more metrics for cluster head election in the clustering mechanism should be studied
EDF _a and GREED	Wang et al. [33], 2014	Maximized weighted throughput of the network	Need to develop the framework for semionline algorithms
CMDP	Zordan et al. [34], 2016	Improved network performance	Modeling of the coupled dynamics of multiple energy-harvesting sensors in a multi-user scenario should be addressed
MEP	Yang et al. [36], 2014	Increased network lifetime and maintained complete coverage	There is no mobility support (All sensor nodes are stationary)
Chance-constrained stochastic approach	Yang et al. [37], 2019	Enhanced coverage lifetime	*) The accuracy of the solutions depends on the number of sensors. **) The complexity of the algorithm should be investigated.
Approximation approach	Misra et al. [39], 2014	Massive network connectivity	*) Finding the optimal solution for MILP is time expensive. **) The effect of the solution on network lifetime should be measured.
MILP and greedy approach	Mehajabin et al. [40], 2016	Increased connectivity network	The computational complexity is very high for larger networks.

Conclusion

With the explosive growth of WSNs, the energy consumption of wireless nodes has increased significantly. Charging or replacing batteries of wireless sensor nodes is either impossible or unpracticable. To deal with these issues, energy harvesting appears as a promising solution which powers batteries by scavenging energy from the ambient environment. Providing wireless devices with energy harvesting capability increases their lifetime. However, it brings new challenges to design efficient communication systems.

This paper presents a survey about energy harvesting in Wireless Sensor Networks. We first present the concept of energy harvesting. Second, we take a close look at Energy-Harvesting Wireless Sensor Networks. We explain why providing energy harvesting capability to sensors nodes is important. Afterwards, we discuss different algorithms and protocols used to save energy consumption in energy harvesting sensor networks. We

explicit their design strategies /working principles and also highlight their merits and their shortcomings.

The algorithms and protocols studied are heuristic based. They try to optimize the energy consumption of wireless nodes and make the best of use of the available energy. However, the produced solutions may not be optimal. They face many challenges such as computational complexity, high overhead, lack of providing coordination between the energy harvesting system and prediction method and no mobility support. Those challenges remain open for future research in order to push the technology further.

References

- [1] Y. Chen, Energy Harvesting Communications: Principles and Theories, Wiley, 2019.
- [2] S.P. Beeby, Z. Cao, A. Almussallam, Kinetic, thermoelectric and solar energy harvesting technologies for smart textiles, *Multidiscip. Know-How Smart-Textiles Dev.* (2013) 306–328.

- [3] A. Kansal, J. Hsu, S. Zahedi, M.B. Srivastava, Power management in energy harvesting sensor networks, *ACM Trans. Embed. Comput. Syst.* 6 (2007) 32--es.
- [4] N. Dang, E. Bozorgzadeh, N. Venkatasubramanian, Chapter 6 - Energy Harvesting for Sustainable Smart Spaces, in: A. Hurson, A. Memon (Eds.), Elsevier, 2012: pp. 203–251.
- [5] K.Z. Panatik, K. Kamardin, S.A. Shariff, S.S. Yuhaniz, N.A. Ahmad, O.M. Yusop, S. Ismail, Energy harvesting in wireless sensor networks: A survey, in: 2016 IEEE 3rd Int. Symp. Telecommun. Technol., 2016: pp. 53–58.
- [6] J. Singh, R. Kaur, D. Singh, Energy harvesting in wireless sensor networks: A taxonomic survey, *Int. J. Energy Res.* 45 (2021) 118–140.
- [7] S. Sudevalayam, P. Kulkarni, Energy Harvesting Sensor Nodes: Survey and Implications, *IEEE Commun. Surv. Tutorials.* 13 (2011) 443–461.
- [8] N. Dang, E. Bozorgzadeh, N. Venkatasubramanian, Energy Harvesting for Sustainable Smart Spaces, *Adv. Comput.* 87 (2012) 203–251.
- [9] A. Idrissi, F. Yakine, Multicast routing with quality of service constraints in the ad hoc wireless networks, *J. Comput. Sci.* (2014).
- [10] F. Yakine, A. Idrissi, Energy efficient routing with network lifetime in wireless ad-hoc networks, in: Int. Conf. Next Gener. Networks Serv. NGNS, 2014.
- [11] D.E. Tiliute, Battery Management in Wireless Sensor Networks, *Elektron. Ir Elektrotehnika.* 76 (2007) 9–12.
- [12] W.K.G. Seah, Z.A. Eu, H.-P. Tan, Wireless sensor networks powered by ambient energy harvesting (WSN-HEAP) - Survey and challenges, in: 2009 1st Int. Conf. Wirel. Commun. Veh. Technol. Inf. Theory Aerosp. Electron. Syst. Technol., 2009: pp. 1–5.
- [13] W. Ye, J. Heidemann, D. Estrin, An energy-efficient MAC protocol for wireless sensor networks, in: Proceedings.Twenty-First Annu. Jt. Conf. IEEE Comput. Commun. Soc., 2002: pp. 1567–1576 vol.3.
- [14] J. Polastre, J. Hill, D. Culler, Versatile Low Power Media Access for Wireless Sensor Networks, in: Proc. 2nd Int. Conf. Embed. Networked Sens. Syst., Association for Computing Machinery, New York, NY, USA, 2004: pp. 95–107.
- [15] W.R. Heinzelman, A. Chandrakasan, H. Balakrishnan, Energy-efficient communication protocol for wireless microsensor networks, in: *Syst. Sci. 2000. Proc. 33rd Annu. Hawaii Int. Conf.*, 2000: pp. 10--pp.
- [16] C. Intanagonwiwat, R. Govindan, D. Estrin, J. Heidemann, F. Silva, Directed Diffusion for Wireless Sensor Networking, *IEEE/ACM Trans. Netw.* 11 (2003) 2–16.
- [17] R.C. Carrano, D. Passos, L.C.S. Magalhaes, C.V.N. Albuquerque, Survey and Taxonomy of Duty Cycling Mechanisms in Wireless Sensor Networks, *IEEE Commun. Surv. Tutorials.* 16 (2014) 181–194.
- [18] Hossam Mahmoud Ahmad, Wireless Sensor Networks Energy Harvesting and Management for Research and Industry, 2020.
- [19] T. Crossbow, Iris Datasheet, (2007). http://www.nr2.ufpr.br/~adc/documentos/iris_datasheet.pdf.
- [20] J.A. Khan, H.K. Qureshi, A. Iqbal, C. Lacatus, Energy management in Wireless Sensor Networks: A survey, *Comput. Electr. Eng.* 41 (2015) 159–176.
- [21] I. Crossbow Technology, MICAZ Datasheet, (2008) 4–5. http://courses.ece.ubc.ca/494/files/MICAZ_Datasheet.pdf.
- [22] Memsic, TelosB datasheet, (2013). http://www.memsic.com/userfiles/files/DataSheets/WSN/telosb_datasheet.pdf.
- [23] P. SunSPOT, SunSpot datasheet, (n.d.). <https://www.sunspotdev.org/about.html>.
- [24] S. Ulukus, A. Yener, E. Erkip, O. Simeone, M. Zorzi, P. Grover, K. Huang, Energy Harvesting Wireless Communications: A Review of Recent Advances, *IEEE J. Sel. Areas Commun.* 33 (2015) 360–381.
- [25] F.K. Shaikh, S. Zeadally, Energy harvesting in wireless sensor networks: A comprehensive review, *Renew. Sustain. Energy Rev.* 55 (2016) 1041–1054.
- [26] D.K. Sah, T. Amgoth, Renewable energy harvesting schemes in wireless sensor networks: A Survey, *Inf. Fusion.* 63 (2020) 223–247.
- [27] F. Li, M. Xiong, L. Wang, H. Peng, J. Hua, X. Liu, A novel energy-balanced routing algorithm in energy harvesting sensor networks, *Phys. Commun.* 27 (2018) 181–187.
- [28] Z.A. Eu, H.P. Tan, W.K.G. Seah, Opportunistic routing in wireless sensor networks powered by ambient energy harvesting, *Comput. Networks.* 54 (2010) 2943–2966.
- [29] A. Mostafa, K. Hassan, Robust energy harvesting aware clustering with fuzzy petri net reasoning algorithm, in: 2014 IEEE 10th Int. Conf. Wirel. Mob. Comput. Netw. Commun., 2014: pp. 378–383.
- [30] S.M. Bozorgi, A. Shokouhi Rostami, A.A.R. Hosseiniabadi, V.E. Balas, A new clustering protocol for energy harvesting-wireless sensor networks, *Comput. Electr. Eng.* 64 (2017) 233–247.
- [31] M.M. Afsar, M. Younis, A load-balanced cross-layer design for energy-harvesting sensor networks, *J. Netw. Comput. Appl.* 145 (2019) 102390.
- [32] G. Anastasi, M. Conti, M. Di Francesco, A. Passarella, Energy conservation in wireless sensor networks: A survey, *Ad Hoc Networks.* 7 (2009) 537–568.
- [33] H. Wang, J.X. Zhang, F. Li, Worst-case

- performance guarantees of scheduling algorithms maximizing weighted throughput in energy-harvesting networks, *Sustain. Comput. Informatics Syst.* **4** (2014) 172–182.
- [34] D. Zordan, T. Melodia, M. Rossi, On the Design of Temporal Compression Strategies for Energy Harvesting Sensor Networks, *IEEE Trans. Wirel. Commun.* **15** (2016) 1336–1352.
- [35] S. Meguerdichian, F. Koushanfar, M. Potkonjak, M.B. Srivastava, Coverage problems in wireless ad-hoc sensor networks, in: Proc. IEEE INFOCOM 2001. Conf. Comput. Commun. Twent. Annu. Jt. Conf. IEEE Comput. Commun. Soc. (Cat. No.01CH37213), 2001: pp. 1380–1387 vol.3.
- [36] C. Yang, K.-W. Chin, A novel distributed algorithm for complete targets coverage in energy harvesting wireless sensor networks, in: 2014 IEEE Int. Conf. Commun., 2014: pp. 361–366.
- [37] C. Yang, K.-W. Chin, Y. Liu, J. Zhang, T. He, Robust Targets Coverage for Energy Harvesting Wireless Sensor Networks, *IEEE Trans. Veh. Technol.* **68** (2019) 5884–5892.
- [38] M. Younis, K. Akkaya, Strategies and techniques for node placement in wireless sensor networks: A survey, *Ad Hoc Networks.* **6** (2008) 621–655.
- [39] S. Misra, N.E. Majd, H. Huang, Approximation Algorithms for Constrained Relay Node Placement in Energy Harvesting Wireless Sensor Networks, *IEEE Trans. Comput.* **63** (2014) 2933–2947.
- [40] N. Mehajabin, M.A. Razzaque, M.M. Hassan, A. Almogren, A. Alamri, Energy-sustainable relay node deployment in wireless sensor networks, *Comput. Networks.* **104** (2016) 108–121.