Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-7, Issue-9, September 2025
DOI: 10.53469/jrse.2025.07(09).02

Efficient Strategies for Wireless Systems

Kanav Bhargava

bhargava786@gmail.com

Abstract: ***Wireless Sensor Networks (WSNs) are cutting-edge technology with vast potential for future applications. Sensor nodes in these networks are limited by energy constraints, relying on batteries with restricted capacity that can impact their longevity and mobility. To combat this issue, energy harvesting technology offers a solution by replenishing node batteries through environmental resources. This study delves into the concept of energy harvesting technology (EH) and its application in Energy-Harvesting for Wireless Sensor Networks (EH-WSN). Various strategies from existing literature are evaluated for reducing energy consumption in energy harvesting sensor networks. The review analyzes protocol design approaches and operational principles, as well as highlighting the strengths, weaknesses, and potential research avenues in this field.***

Keywords: Energy Efficiency (EE), Wireless Sensor Networks (WSNs), Energy Harvesting, Sleep Mode Techniques, Smart Grid Communications, Energy-Aware Routing, Power Consumption

1. Introduction

Over the past few decades, there has been remarkable progress in wireless communications, bringing significant convenience to our daily lives. Unlike traditional wired transmission, wireless data transmission eliminates the need for cumbersome wires and cables. However, the limitations of conventional wireless systems are primarily attributed to the batteries that power wireless nodes, impacting their mobility and lifespan and hindering their widespread deployment.

In recent years, Green Communication (GC) has garnered considerable interest as an innovative approach to reducing greenhouse gas emissions. This strategy promotes the utilization of renewable resources such as solar energy, wind energy, and other sustainable sources to power wireless communications systems. Additionally, Wireless Power Transfer (WPT) has emerged as a cutting-edge technology enabling the transmission of electrical power without the constraints of wires or physical contacts.

Recent attention has been drawn to the concept of Green Communication (GC) to combat greenhouse emissions by harnessing solar and wind energy, as well as other renewable resources. The emergence of wireless power transfer (WPT) has also gained popularity, enabling the transmission of electrical power without the need for wires or direct contact. Considering these advancements, it is crucial to incorporate wireless power transfer and energy harvesting (EH) to fully leverage the capabilities of wireless communication [1].

The study provides an extensive overview of energy harvesting techniques in EH-WSNs, detailing the fundamental concepts of EH and the rationale for implementing energy harvesting systems in wireless sensor nodes. Recent research on energy conservation in EH-WSNs is synthesized, focusing on operational principles and suggesting areas for enhancement. The paper is structured as follows: Section 2 delves into the essence of energy harvesting, covering applications, attributes, and sources. Section 3 examines the significance of energy harvesting in WSNs and classifies sources pertinent to WSNs. Section 4 explores diverse energy management strategies in EH-WSNs, outlining design approaches, benefits, and drawbacks.

2. Energy Harvesting (EH)

Energy harvesting, also known as energy scavenging, is a method utilized to mitigate the issue of constrained node longevity. This technique involves the gathering and transformation of ambient energy into electrical energy for powering autonomous electronic devices or circuits [2]. The domain of energy harvesting materials and systems has become a prominent area of study with ongoing growth and development. Harvesters are applied across a wide array of applications such as:

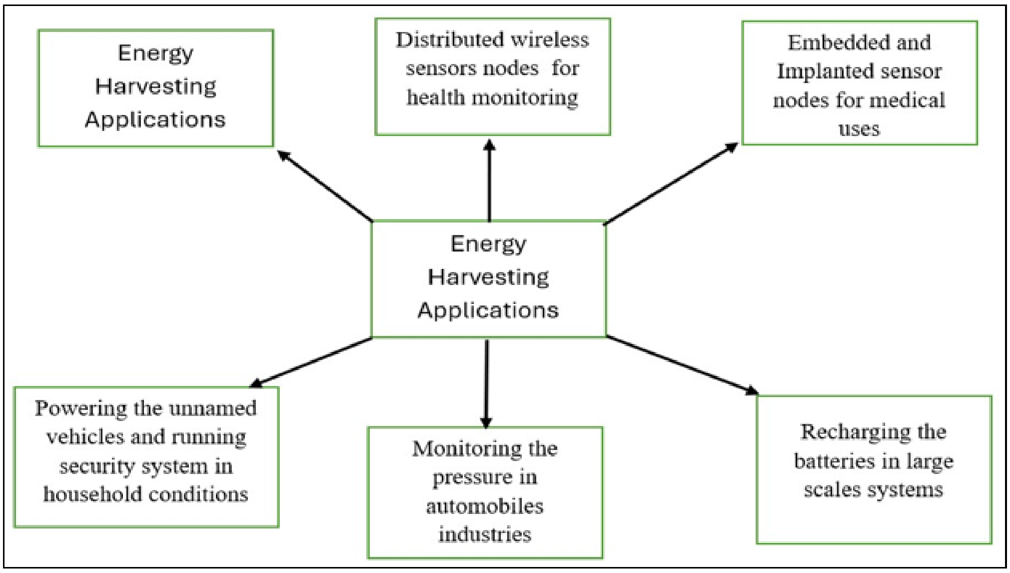

Figure 1: Application of Energy Harvesting Systems

2.1 Sources of Energy Harvesting:

In the field of wireless communications, there exists a variety of energy sources that can be harnessed for power. These sources can be categorized into four groups based on their controllability and predictability properties [3]. Controllability refers to the degree to which a system can manipulate its energy sources, while predictability involves assessing the ability to forecast the behavior of these sources [4].

- The energy sources discussed are uncontrollable and unpredictable, making it challenging to harness them for energy production at specific times. Mechanical vibration is a prime example of such a source. While technologies like piezoelectric and electromagnetic harvesters can convert vibration into electricity, the difficulty lies in accurately predicting when and where the vibration will occur, let alone intentionally generating it [1].
- Although they cannot be controlled to produce energy at specific times and locations, certain energy sources exhibit predictable behavior within a margin of error. For example, solar energy relies on diurnal and seasonal cycles that can be modeled to forecast availability, despite the inability to control the movement of the sun or the weather[3.]
- **Fully Controllable**: Energy production can be initiated at the user's discretion. For instance, a handheld flashlight can generate power through user shaking whenever and wherever necessary.
- **Partially Controllable**: System designers or users have some influence over energy generation, although the resulting behavior may not be completely deterministic.

2.2 Types of Energy harvesting

The energy harvesting system can be classified based on the type of energy harvested as follows [5,6]:

- **Mechanical Energy:** This type of energy is obtained from various sources including vibration, motion, stress, pressure, or strain, which is then converted into electricity.
- **Wind Energy:** Wind or air can be harnessed to generate energy through this method.
- **Solar/Light Energy**: Photons from a light source are converted into electricity using photovoltaic cells. When photons from the light source reach the photovoltaic cell, electrons are released to generate electricity.
- **Electromagnetic Energy:** This energy is derived from the surrounding environment, such as radiation from cellular base stations, TV transmitters, WIFI routers, or dedicated power transmitters**.**
- Body energy is generated through the movement of body parts and the natural regulation of body temperature.
- Hydropower is harnessed from the movement of flowing water and ocean tides.
- Geothermal energy is produced by the heat within the Earth's core.
- Biomass energy is derived from biodegradable waste, human urine, and various chemical and biological sources.

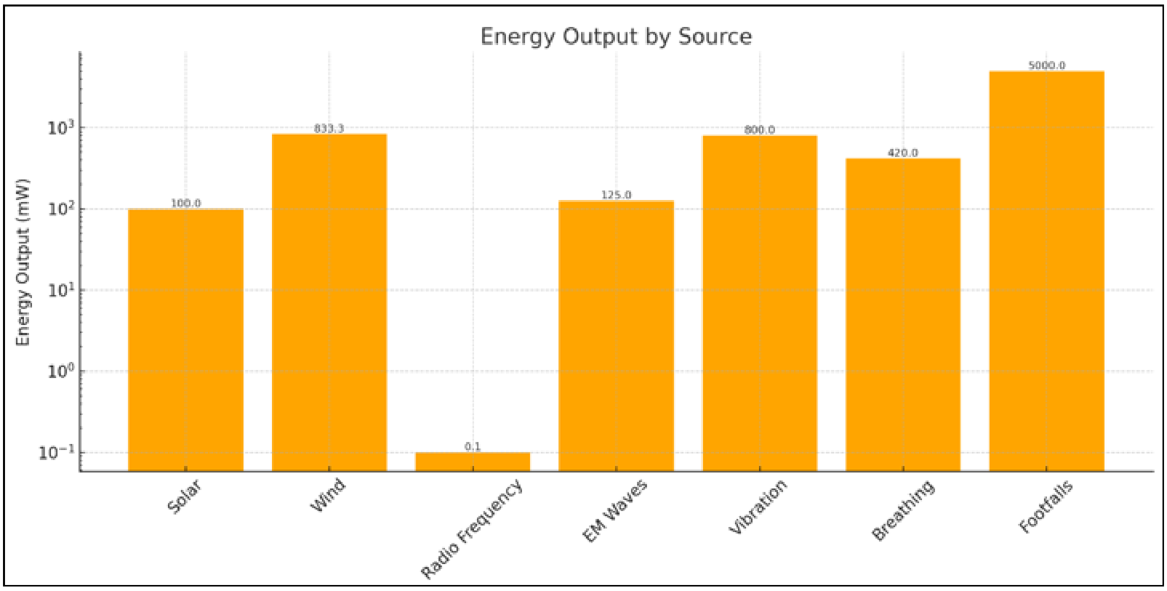

Figure 2: Energy Harvesting Graphs

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

In the field of sensor networks, the Energy Harvesting Wireless Sensor Network, abbreviated as EH-WSN, plays a crucial role in collecting data efficiently.

3.1 Motivation for Energy Harvesting Wireless Communications

In recent years, there has been a significant focus on Wireless Sensor Networks (WSNs). These networks have become widespread and are being used in various applications such as the internet of things, cyber physical systems, and other emerging fields. In scenarios where the system needs to function for long periods, energy consumption becomes a critical limitation.

The main criteria for assessing energy efficiency in Wireless Communications are now focused on network lifetime and energy performance. Various techniques have been introduced to minimize energy consumption and enhance network longevity [9, 10]. WSN nodes are typically deployed in remote and inaccessible locations, making it impractical to regularly recharge or replace their depleted batteries. If a node's energy source depleted, it will disconnect from the network unless energy is replenished or a harvesting mechanism is introduced to bridge the gap [11]. Even when not in operation, battery drain can occur due to current leakages, and packaging defects resulting from prolonged usage may pose environmental risks [12].

Numerous studies have addressed the issue of extending the lifespan of battery-powered sensor nodes. Some examples include energy-efficient MAC protocols such as SMAC [13] and BMAC [14], as well as efficient protocols for routing and data dissemination [15, 16]. Additionally, duty-cycling strategies have been proposed [17]. These methods aim to optimize energy consumption in sensor nodes to prolong their lifespan. However, despite these efforts, the lifespan of sensor nodes remains limited. While these techniques may enhance application lifespan and delay the need for battery replacements, they do not fully address the constraints associated with energy limitations.

Optimizing all performance metrics of a Wireless Sensor Network (WSN) simultaneously is not feasible. Increasing the battery capacity will result in higher costs, weight, and size. A lower duty-cycle will lead to reduced sensing reliability. Additionally, a higher transmission range requires more power, while a lower transmission range utilizes routing paths with multiple hops, resulting in increased power consumption at each hop [18].

Enabling wireless devices with the capability to harvest energy from environmental sources, whether natural or man-made, provides numerous benefits for wireless networking. These include energy self-sustainability, continuous operation, decreased reliance on conventional energy sources and subsequent reduction in carbon footprint, elimination of battery replacement and freedom from tethering to electricity grids for enhanced mobility. Additionally, this technology allows for deployment of devices in difficult-to-access locations such as inside buildings, remote rural areas, and even within the human body [24].

Energy harvesting strategies can effectively manage the balance between performance metrics and the longevity of sensor nodes, as previously addressed. This involves predicting the size and frequency of the available energy source and dynamically adjusting parameters to prevent energy depletion before the next recharge cycle. The assessment of the energy source's frequency and size, as well as determining which parameters to adjust to prevent premature battery depletion, poses a significant challenge [7].

3.2 Energy Harvesting sources in WNS:

Energy harvesting sources for wireless sensor networks (WSN) can be categorized as ambient or external sources [25]. Ambient sources are derived from the immediate surroundings and include RF-based energy (Radio Frequency), solar energy, kinetic energy from motion, and thermal energy. On the other hand, external sources are specifically implemented for the purpose of energy harvesting.

The examples of ambient/external sources for WSN and their subcategories are illustrated in Figure 3. Not all energy sources can be utilized in wireless communication systems due to constraints such as size, mobility, or power limitations of wireless nodes. Therefore, selecting the suitable source for energy harvesting in the design of energy harvesting wireless communication systems is crucial. Figure 4 displays the prevalent energy sources employed in energy harvesting wireless communications.

Solar energy is easily accessible and reliable, thanks to its predictable nature based on diurnal and seasonal cycles. Its compatibility with small solar panels makes it a highly promising source of energy for wireless sensor nodes [3].

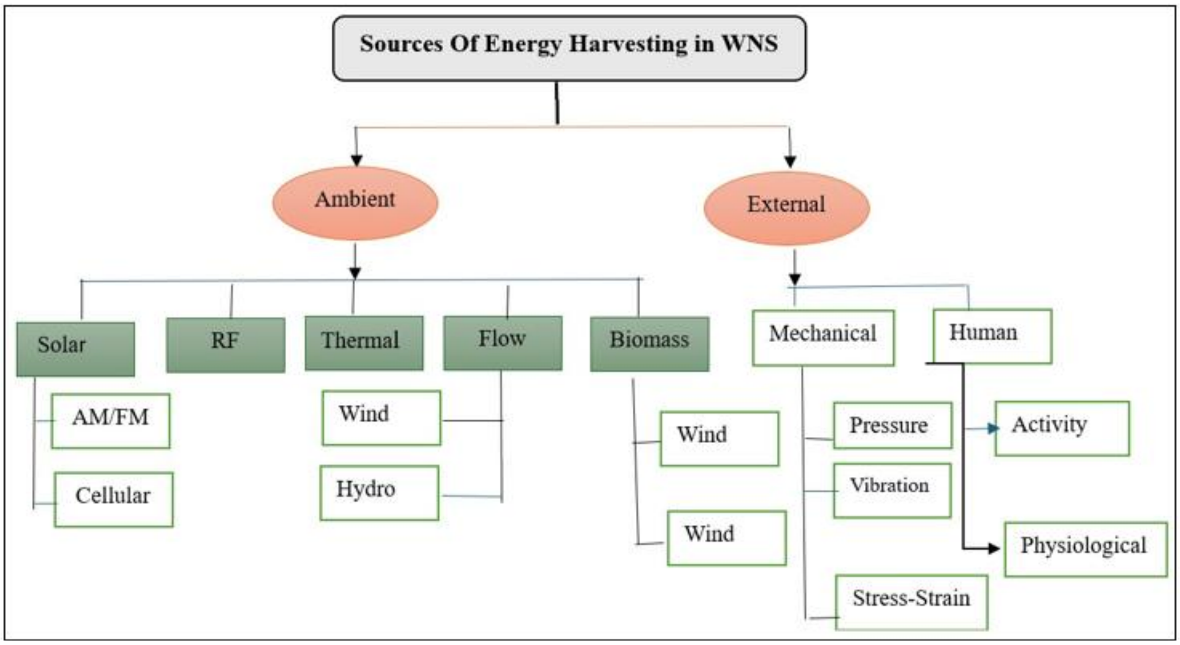

Figure 3: Sources of energy Harvesting in WNS

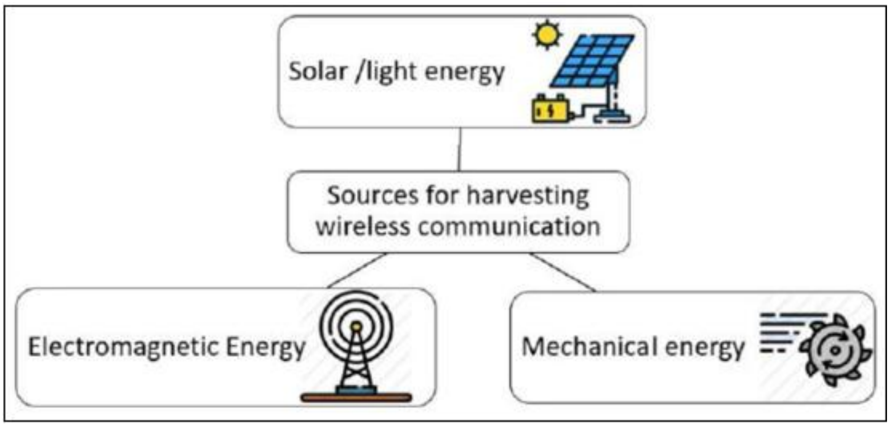

Figure 4: Various commonly utilized energy sources for wireless communications in Energy Harvesting (EH) technology are as follows

4. Exploring energy management strategies for Wireless Sensor Networks (WSNs)

The following section explores various strategies utilized to reduce energy usage in energy harvesting sensor networks. These strategies are categorized into four groups based on Clustering and routing, energy balancing, coverage-awareness, and node placements as outlined in reference [26].

4.1 Schemes based on Clustering and Routing

The objective of clustering involves partitioning the network into clusters, each consisting of a cluster head (CH) and several cluster members. A crucial aspect of the clustering protocol is determining the appropriate CH. This selection can be based on the nodes' energy levels or on minimizing the communication range (Rc) of the cluster members.

Routing involves determining the best path from one node to another, whether between sensor nodes or from a sensor node to a sink. Developing an energy-efficient routing protocol is a complex task due to the high energy consumption involved. The goal of energy harvesting WSN-based routing protocols is to prolong network lifespan and enhance throughput (27).

In [28], the authors developed the EHOR (Energy Harvesting Opportunistic Routing) protocol, which operates using only ambient energy harvesters (WSN-HEAP) without the need for batteries. Nodes select optimal forwarding candidates based on proximity to the sink and their remaining energy levels in the surrounding area. These potential forwarders are segmented into regions, with the closest to the sink resending a packet upon receipt. EHOR has been successful in enhancing the network's goodput and overall efficiency.

4.2 Schemes for Energy Balancing

Energy balancing is a key concern within Wireless Sensor Networks (WSN) as it plays a crucial role in preventing premature depletion of nodes by effectively managing their traffic load. Uneven energy consumption among sensor nodes can lead to inconsistencies in their lifetimes. Various methods, including dynamic routing, duty cycling, scheduling techniques, time synchronization, and minimizing delay, have been implemented for energy balancing in WSN [26, 32].

In [33], the authors explored the issue of scheduling weighted packets with deadlines in an energy-harvesting sensor node. They introduced an optimal offline framework and deterministic online algorithms to maximize the weighted throughput, which represents the total value of transmitted packets. Each packet is constrained by energy harvesting and deadlines.

The article discusses a constrained formulation utilizing MDP (Markov Decision Process) to reduce data compression distortion and manage energy consumption. The algorithm aims to regulate lossy data compression in scenarios of signal fading [34].

4.3 Implementing Coverage Awareness Strategies

One of the key factors affecting network performance in Wireless Sensor Networks (WSN) is sensor coverage. In addition to location calculation, tracking, and deployment, coverage plays a crucial role in determining the sensing capability of nodes. By establishing a geometric relationship between target points and sensor nodes, sensor coverage awareness measures the quality of service provided by a sensor network. It defines the effectiveness of sensors in monitoring a specified area.

The authors introduced a distributed algorithm in [36] to guarantee coverage in wireless sensor networks (WSNs) with energy harvesting capabilities. The proposed protocol, known as MEP (Maximum Energy Protection), specifically tackled the DMLC-EH issue (Distributed Maximum Lifetime Coverage with Energy Harvesting). The core concept behind MEP is to cyclically activate sensors to create a minimal set that can cover all targets, ultimately maximizing the network's lifetime.

The study described in reference [37] introduced a durable coverage area strategy for energy harvesting wireless sensor networks. Each sensor node is outfitted with solar panels and strategically placed within a designated sensing area to encompass the desired points. The proposed methodology calculates the optimal sleep and wake schedules for the sensor nodes, guaranteeing that all target areas are monitored by at least one sensor node with a specified probability of success ($1-\epsilon$), where ϵ represents the likelihood of coverage failure or energy depletion.

4.4 Strategies for Positioning Nodes

Node placement is critical for ensuring a reliable connection between sensor nodes within a network. Utilizing node placement schemes can facilitate the establishment of an efficient link between sensor nodes and the base station. This task is particularly complex as it is recognized as NP-Hard for the majority of sensor deployment scenarios [38].

The constrained relay node placement problem in Energy Harvesting WSNs (EH-CRNP) was addressed by authors in [39]. They introduced a mixed-integer linear program (MILP) approximation to strategically place relay nodes in locations with optimal energy harvesting potential. Each sensor node is assigned a weight value based on its energy harvesting capabilities, ensuring efficient connectivity and survivability.

5. Summary

Summary of Energy Management Techniques for EH-WSN
In this segment, a variety of energy management techniques for EH-WSN have been introduced. The design strategies and operational principles of these techniques have been outlined, along with a discussion on their advantages and limitations.

In clustering-routing based schemes the selection of the cluster head is typically determined solely by the residual energy of the node, without considering the predicted energy harvesting capabilities. This raises the question of whether these schemes can effectively support energy harvesting in scenarios where the energy harvesting system is unpredictable and challenging to forecast.

The energy balancing schemes presented in references aim to enhance network performance by redistributing energy among sensor nodes. However, these schemes do not take into account energy harvesting capabilities. While the constructed routes effectively balance energy, the prediction of harvested energy is not factored into their construction.

Coverage-based algorithms have been suggested to extend coverage lifetime, but they do not offer integration with the energy harvesting system. Similarly, node placement techniques have successfully achieved optimal node placement, but they also do not coordinate with the energy harvesting system.

6. Conclusion

The rise of WSNs has led to a notable increase in the energy consumption of wireless nodes. Recharging or replacing batteries for these sensor nodes is often not a feasible option. Energy harvesting emerges as a promising solution to address these challenges, as it allows for the powering of batteries by harnessing energy from the surrounding environment. Equipping wireless devices with energy harvesting capabilities can extend their lifespan but also presents new challenges in designing efficient communication systems.

This paper discusses energy harvesting in Wireless Sensor Networks. We begin by introducing the concept of energy harvesting. Next, we delve into the specifics of Energy-Harvesting Wireless Sensor Networks and the significance of providing energy harvesting capabilities to sensor nodes. Furthermore, we explore various algorithms and protocols utilized to reduce energy consumption in energy harvesting sensor networks.

We examine the design strategies and working principles of these algorithms and protocols, showcasing their strengths and weaknesses. The heuristic-based approaches aim to enhance the energy efficiency of wireless nodes and maximize energy utilization. However, the solutions generated may not always be optimal. Challenges including computational complexity, excessive overhead, insufficient coordination between energy harvesting systems and prediction methods, as well as a lack of mobility support, persist. These challenges present opportunities for future research in advancing technology in this field.

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 Elektrotechnika. 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.