Classifying WSNs based on their energy management and communication synchronization mechanisms

Pablo Nascimento
Department of Informatics
Pontifical Catholic University of Rio de Janeiro
Rio de Janeiro, Brazil
pnascimento@inf.puc-rio.br

Adriano Branco
Department of Informatics
Pontifical Catholic University of Rio de Janeiro
Rio de Janeiro, Brazil
abranco@inf.puc-rio.br

Markus Endler
Department of Informatics
Pontifical Catholic University of Rio de Janeiro
Rio de Janeiro, Brazil
endler@inf.puc-rio.br

***Abstract*—Wireless Sensor Networks (WSNs) are increasingly deployed across diverse applications, from environmental monitoring and healthcare to military and commercial use. These networks face significant energy challenges, as battery constraints often limit operational longevity and complicate maintenance of the WSN nodes, especially in remote areas. While techniques like duty cycling can extend battery life, they do not eliminate the need for battery replacement or mitigate the environmental impact of battery use. As a promising alternative, energy harvesting (EH) allows nodes to gather power from their surroundings, enabling WSNs to operate autonomously with reduced maintenance requirements. However, EH presents new challenges due to the intermittent and unpredictable nature of energy harvesting, which creates asynchrony in communication and complicates intra-WSN data transfer.**

This study proposes a two-dimensional classification framework to evaluate existing WSN approaches based on energy management and communication synchronization strategies. By categorizing current solutions into energy adaptation and synchronization techniques, we aim to determine whether they address quality of service (QoS) issues directly or indirectly. This classification also highlights unexplored combinations, offering insights into potential new paradigms for more efficient and resilient WSNs. Some studies have been conducted in this field, and future work will compare them by analyzing their communication methods related to energy management strategies in a survey.

***Index Terms*—WSN, Energy Harvesting, Survey, Communication Issues, Communication Synchronism, Energy Management.**

I. Introduction

Wireless Sensor Networks (WSNs) are increasingly used in various sectors of modern society and have demonstrated their effectiveness in various applications. These include greenhouse monitoring, livestock management, underwater sensing, vehicular ad-hoc networks, wireless body area networks, environmental monitoring, and the observation of forests and habitats. Additionally, WSNs are valuable in health monitoring and military, industrial, and commercial contexts [1].

In a WSN, each node collects and transmits data to neighboring nodes, often routing the information to a base station. Batteries typically power these networks, simplifying device design and operation since power is consistently available for data acquisition and communication. However, battery power presents limitations, including constraints on device size [2], maintenance logistics [3], potential chemical contamination [4], and performance issues under conditions like high humidity [5] and low temperatures [6].

Radio-frequency communication is typically the primary drain on battery power [7], as transmitting, receiving, or just simply listening for incoming data demands some energy consumption. To extend battery life, the duty cycling technique is commonly employed [8], allowing devices to periodically switch to *idle* or *low-power modes*. Duty cycling decreases energy consumption [9] and ensures that data is retransmitted for a period sufficiently long to all neighboring nodes to receive that message. However, it also increases communication latency, as when the nodes wake up, the data source, one of its neighboring nodes, is already transmitting for a while [10]. This technique can be adapted to the specific requirements of each application, effectively balancing energy savings with communication needs.

Despite using the duty cycle technique, battery replacement is still necessary when the charge is depleted [11]. This method does not resolve batteries' inherent chemical limitations or environmental impacts. Harvesting energy from the device's environment can solve these challenges. This approach allows the device to operate in conditions that would otherwise hinder battery performance to maintain its operation [12]. Harvesting energy from the environment instead of using batteries is a design shift that allows the expansion of the potential applications of Wireless Sensor Networks (WSNs), leading to a reduced need for frequent maintenance and facilitating deployment in remote or hard-to-access locations.

Energy Harvesting (EH) presents distinct challenges. The energy harvested is often transient [13], and its availability can fluctuate significantly over time and across different locations [14]. This means that a device may require more power than it can currently harvest. Consequently, designs for EH devices must manage energy flow carefully, especially regarding the architecture of the EH system.

The System Support for Computation can be categorized into three stages. In the *Energy-neutral stage*, the energy harvested is equal to or greater than the energy consumed over a prolonged period. This stage typically relies on an energy storage mechanism [15]. In the *Power-neutral stage*, the power generated matches the power consumed in real-time and may not require energy storage [16]. Finally, in the *Intermittent stage*, the energy storage no longer provides a continuous power supply for the system. As a result, the system may enter idle mode or shut down entirely until enough energy is harvested to power it on and resume operation.

Several design and intermittency challenges exist in WSNs, primarily due to the unpredictability of energy harvesting opportunities and the physical limitations of energy storage. Intermittency should be viewed as an unavoidable factor that impacts each device differently. Variations in energy and charging lead to devices becoming active at different times [17]. For example, two similar solar-powered energy harvesting (EH) devices might charge at different rates due to differences in sunlight exposure, resulting in misaligned active periods that hinder direct communication between them.

Data transfer presents a significant challenge in wireless sensor networks (WSNs). Communication requires considerable energy, meaning devices must have sufficient power to complete a data transfer [18]. Additionally, they depend on another device that meets these same energy requirements and is active simultaneously [19]. These complexities create numerous research opportunities, which are being actively explored worldwide.

A key area of research is improving the network's quality of service. This can be accomplished by minimizing asynchrony between nodes, either through direct synchronization techniques or by increasing the likelihood of nodes being active simultaneously.

In the next section, we will describe the classification that will be used in the upcoming survey.

II. Classification

In this section, we will clarify the classification for our future survey. We will outline the aspects we intend to evaluate and the scenarios we wish to categorize.

Based on operational data, the energy management dimension examines how nodes can adjust their power consumption. In the most basic scenario, nodes operate whenever there is sufficient energy without intentional power usage management. A more advanced approach involves nodes that leverage insights into both energy consumption and harvesting patterns, allowing them to activate when conditions are likely to favor successful operation selectively. The most sophisticated level is characterized by nodes that optimize their activity phase based on predefined metrics, such as throughput or latency, effectively aligning their energy usage with these specific goals.

In parallel, the communication synchronization dimension focuses on how nodes align their active phases to communicate effectively with neighboring nodes. In one scenario, nodes rely on opportunistic synchronization, attempting communication during each active period and establishing connections by chance. In a more structured approach, nodes schedule their active phases based on knowledge of each other's activity patterns, which improves synchronization and reduces communication failures. The most precise approach involves interrupt-driven synchronization, where nodes use interruption signals to directly wake each other directly, ensuring alignment for timely data transfer.

This classification aims to clarify whether these strategies enhance network quality of service directly or indirectly. Additionally, it highlights possible unexplored combinations, offering valuable insights for future research and innovation in developing more energy-efficient and reliable WSNs.

We believe that this classification will help identify whether the solutions address quality of service issues directly or indirectly. Additionally, we hope it will highlight the potential for new approaches or paradigms. Some studies have been conducted in this field, and future work will compare them by analyzing their communication methods related to energy management strategies.

References

[1] A. Ali, Y. Ming, S. Chakraborty, and S. Iram, "A comprehensive survey on real-time applications of wsn," *Future internet*, vol. 9, no. 4, p. 77, 2017.

[2] J. A. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive computing*, vol. 4, no. 1, pp. 18–27, 2005.

[3] G. V. Merrett and B. M. Al-Hashimi, "Energy-driven computing: Rethinking the design of energy harvesting systems," in *Design, Automation & Test in Europe Conference & Exhibition (DATE), 2017*, pp. 960–965, IEEE, 2017.

[4] J. Dorris, B. H. Atieh, and R. C. Gupta, "Cadmium Uptake by Radishes from Soil Contaminated with Nickel-Cadmium Batteries: Toxicity and Safety Considerations," *Toxicology Mechanisms and Methods*, vol. 12, pp. 265–276, Jan. 2002. Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/15376520208951163.

[5] M. Afanasov, N. A. Bhatti, D. Campagna, G. Caslini, F. M. Centonze, K. Dolui, A. Maioli, E. Barone, M. H. Alizai, J. H. Siddiqui, and L. Mottola, "Battery-less zero-maintenance embedded sensing at the mithræum of circus maximus," in *Proceedings of the 18th Conference on Embedded Networked Sensor Systems*, SenSys '20, (New York, NY, USA), p. 368–381, Association for Computing Machinery, 2020.

[6] S. Zhang, K. Xu, and T. Jow, "A new approach toward improved low temperature performance of li-ion battery," *Electrochemistry communications*, vol. 4, no. 11, pp. 928–932, 2002.

[7] M. Nardello, H. Desai, D. Brunelli, and B. Lucia, "Camaroptera: A batteryless long-range remote visual sensing system," in *Proceedings of the 7th International Workshop on Energy Harvesting & Energy-Neutral Sensing Systems*, pp. 8–14, 2019.

[8] T. Rault, A. Bouabdallah, and Y. Challal, "Energy efficiency in wireless sensor networks: A top-down survey," *Computer networks*, vol. 67, pp. 104–122, 2014.

[9] X. Fafoutis, L. Marchegiani, A. Elsts, J. Pope, R. Piechocki, and I. Craddock, "Extending the battery lifetime of wearable sensors with embedded machine learning," in *2018 IEEE 4th World Forum on Internet of Things (WF-IoT)*, (Singapore), pp. 269–274, IEEE, Feb. 2018.

[10] Q. Chen, H. Gao, Z. Cai, L. Cheng, and J. Li, "Distributed low-latency data aggregation for duty-cycle wireless sensor networks," *IEEE/ACM Transactions On Networking*, vol. 26, no. 5, pp. 2347–2360, 2018.

[11] Z. Cai, Q. Chen, T. Shi, T. Zhu, K. Chen, and Y. Li, “Battery-Free Wireless Sensor Networks: A Comprehensive Survey,” *IEEE Internet of Things Journal*, vol. 10, pp. 5543–5570, Mar. 2023. Conference Name: IEEE Internet of Things Journal.

[12] D. Balsamo, A. S. Weddell, G. V. Merrett, B. M. Al-Hashimi, D. Brunelli, and L. Benini, “Hibernus: Sustaining Computation During Intermittent Supply for Energy-Harvesting Systems,” *IEEE Embedded Systems Letters*, vol. 7, pp. 15–18, Mar. 2015. Conference Name: IEEE Embedded Systems Letters.

[13] A. Branco, L. Mottola, M. H. Alizai, and J. H. Siddiqui, “Intermittent asynchronous peripheral operations,” in *Proceedings of the 17th Conference on Embedded Networked Sensor Systems*, SenSys ’19, (New York, NY, USA), pp. 55–67, Association for Computing Machinery, Nov. 2019.

[14] D. N. Fry, D. E. Holcomb, J. K. Munro, L. C. Oakes, and M. Matson, “Compact portable electric power sources,” tech. rep., Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 1997.

[15] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, “Power management in energy harvesting sensor networks,” *ACM Trans. Embed. Comput. Syst.*, vol. 6, p. 32–es, sep 2007.

[16] B. J. Fletcher, D. Balsamo, and G. V. Merrett, “Power neutral performance scaling for energy harvesting mp-socs,” in *Design, Automation & Test in Europe Conference & Exhibition (DATE), 2017*, pp. 1516–1521, IEEE, 2017.

[17] K. Geissdoerfer and M. Zimmerling, “Learning to Communicate Effectively Between Battery-free Devices,”

[18] S. W. Arms, C. P. Townsend, D. L. Churchill, J. H. Galbreath, and S. W. Mundell, “Power management for energy harvesting wireless sensors,” in *Smart Structures and Materials 2005: Smart Electronics, MEMS, BioMEMS, and Nanotechnology*, vol. 5763, pp. 267–275, SPIE, May 2005.

[19] K. Geissdoerfer and M. Zimmerling, “Bootstrapping Battery-free Wireless Networks: Efficient Neighbor Discovery and Synchronization in the Face of Intermittency,” 2021.