Data-Aware Energy Management in Energy-Harvesting Wireless Sensor Networks

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Abstract

Battery-powered nodes in energy-harvesting wireless sensor networks (EH-WSN) under heavy operational load, require an energy management algorithm to achieve energy-neutral operation (ENO). Existing research focuses on improving the accuracy of the prediction of harvested energy to enforce energy constraints and thereby maximize the duty cycle. In this work, we present three techniques for energy management in EH-WSNs, namely, delayed transmission of data using non-volatile storage, design space exploration (DSE) for optimization of system parameters, and utility-aware decision-making. These techniques are designed to enhance the energy management capabilities of EH-WSNs, allowing for more efficient use of harvested energy and improved application-specific accuracy, while enforcing ENO.

CCS Concepts

• **Computer systems organization → Real-time systems**; **Sensor networks**; • **Hardware → Renewable energy**.

Keywords

IoT, Energy Harvesting, WSN

1 Introduction

In Wireless Sensor Networks (WSN), energy harvesting is used to extend the lifetime of sensor nodes and gateways, allowing for their autonomous deployment in remote locations where replacing batteries is often costly (e.g., in biodiversity monitoring [8]). However, using environmental energy sources such as photovoltaic panels leads to unforeseen fluctuations in the amount of energy harvested over time which do not necessarily align with the variation of workload on the network. For example, an avalanche monitoring application operates continuously day and night, but photovoltaic panels only harvest energy during the day.

Thus, energy management strategies, enforced by an *energy manager* (EM), are essential to ensure that the harvested energy is sufficient to cover the energy consumed by the nodes in the network, while maximizing the application-specific accuracy of the network [5]. This mode of operation is referred to as energy-neutral operation (ENO) [3]. The two surrogate constraints to enforce this mode are (1) that the state of charge of a node at the end of a defined period (in the case of PV panels, typically 24h) is greater or equal than the state of charge of the node at the start of the period and (2) the batteries are never depleted below a certain level.

In this work, we consider the problem of data logging in an EH-WSN under ENO constraints, where sensor nodes transmit data of different sizes at different periods to a gateway which is tasked with periodically transmitting the received sensor data to a cloud server over a power-hungry wireless interface (e.g., LTE) according to a pre-determined schedule (cf. Figure 1). In this context, we try to answer the following research questions:

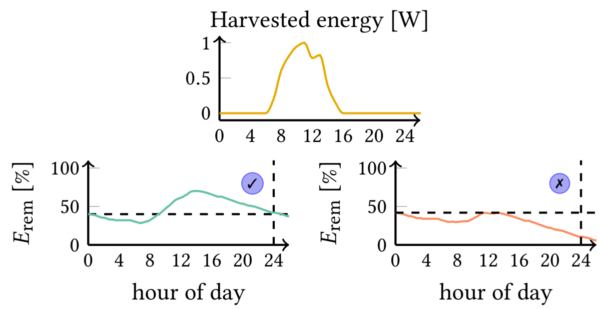


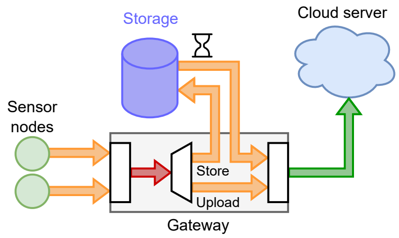
Figure 1: For a given profile of harvested energy, energy neutral operation (ENO) can be achieved ✓ or not ✗ by carefully managing the energy remaining E_{rem} in each node in the network.

- **RQ1:** How can we decide when to store incoming data and delay its upload from the gateway to the cloud?
- **RQ2:** How can the design parameters of a gateway in an EH-WSN be optimized before deployment, given workload and environmental constraints?
- **RQ3:** Can we estimate the importance of data samples based on their value via a utility function, and can we use this utility to decide which data to upload?

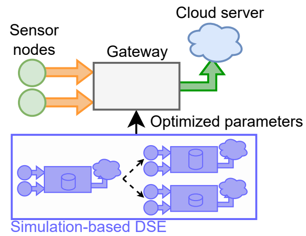
2 Delayed Data Upload

While a gateway is tasked with periodically transmitting the sampled sensor data to the cloud over a power-hungry wireless interface (e.g., LTE), it may not always have sufficient energy available to transmit all the collected data. In such cases, storing the data on non-volatile memory and delaying their transmission until sufficient energy is available can be a viable solution to smoothen energy consumption over time and align it with the energy harvesting patterns.

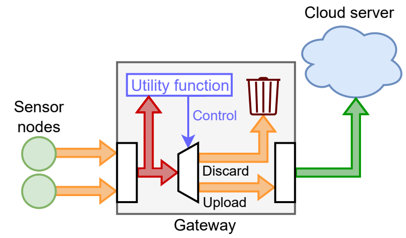
In [4], we present a lightweight file management system designed for gateways in EH-WSN (called *Seque*), alongside energy management techniques that allow for selective transmission of data based on the state of charge of the gateway's battery. The characterization of the energy consumption of each task (storing, transmitting) of the gateway is used to determine whether the gateway can afford to transmit data immediately or whether it should store the data for later transmission. By limiting the access methods to those of a FIFO queue (i.e., enqueue and dequeue), the implementation of Seque is kept simple, with a minimal memory overhead.



(a) Delayed data upload



(b) Simulation-based DSE



(c) Utility-aware selective upload

Figure 2: Overview of the investigated methods of energy management in energy-harvesting wireless sensor networks. Colored arrows indicate data flow, ranging from red (high amount of data) to green (low amount of data).

3 Simulation-Based Design Space Exploration

The application-specific accuracy achieved by an EH-WSN is significantly influenced by design decisions made early in the development process, particularly before system deployment. The parameters of a design include the photovoltaic panel peak power rating, battery capacity, storage capacity, and the choice and configuration of energy management algorithms. These parameters create an extensive design space that requires systematic exploration to identify and select Pareto-optimal design configurations. Furthermore, the conditions of deployment of the EH-WSN, such as the expected workload of the network (i.e., the number of sensor nodes, their sampling periods, and the amount of data generated), and the seasonal sunlight patterns will influence the objective function.

In [6], we present a design space exploration (DSE) framework that explores the design space of an energy-harvesting node embedding multiple sensors. The framework leverages genetic algorithms combined with simulation-based evaluation of the amount of data successfully transmitted to the cloud and the energy neutrality of the node. We demonstrate that the framework can be used to identify Pareto-optimal configurations of the design parameters, as long as the conditions of deployment are identical to those used for the simulation. While it is not part of the publication, the presented framework can be adjusted to explore the design space of a WSN with multiple nodes and gateways, as well as different energy management algorithms.

4 Utility-Aware Selective Upload

In real-world applications, not all collected samples coming from the same sensor are equally important, and some may be more valuable than others [1]. For example, in an anomaly detection scenario, a data sample indicating a potential anomaly is more valuable than a sample that reflects normal behavior. While most of the energy management methodologies for EH-WSNs in the literature do not consider the utility of the data being transmitted, some consider a time-dependent utility function, e.g., whether the data is collected during daytime or during the night [2]. However, these approaches do not consider the utility of the data itself, which can vary significantly even within the same time period.

In [7], we investigate the use of application-specific utility functions for decision-making in energy management algorithms. These functions are designed to quantify the importance of data samples based on their content, allowing the system to prioritize the transmission of more valuable data. In particular, these functions need to be lightweight and fast to compute, as they are used in real-time decision-making. For example, in an anomaly detection scenario, the utility function can assign higher values to data samples that deviate from the average value observed, while assigning lower values to samples that do not. This utility function is then used by the energy manager: if the energy available is not sufficient to transmit all collected data, the energy manager can decide to only transmit data samples with utilities higher than a predetermined threshold and discard the rest.

5 Conclusion and Outlook

With the presented techniques, we manage to significantly improve the accuracy of the EH-WSN while still ensuring energy-neutral operation, compared to related approaches who, e.g., did not use non-volatile storage or considered that all data points are equally important. Future works include integrating these techniques into a unified framework and exploring their applicability in more diverse real-world scenarios.

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