Summary of the Paper “Survey of Energy Harvesting Technologies for Wireless Sensor Networks”

Authors: Alexander J. Williams, Matheus F. Torquato, Ian M. Cameron, Ashraf A. Fahmy, and Johann Sienz

I Introduction

In the paper “Survey of Energy Harvesting Technologies for Wireless Sensor Networks” by Alexander J. Williams, Matheus F. Torquato, Ian M. Cameron, Ashraf A. Fahmy, and Johann Sienz, Energy Harvesting (EH) Technologies for Wireless Sensor Networks (WSNs) are surveyed. With the potential to revolutionize WSNs by enabling self-sustaining networks that integrate with energy storage systems, these technologies extend their lifespan and meet energy demands. As Industry 4.0 continues to evolve, EH technologies are poised to play a pivotal role in this industrial transformation.

EH involves extracting wasted energy from the ambient environment and converting it into usable forms for autonomous systems. By scavenging energy through natural or artificial processes, EH provides a solution to the energy challenges faced by WSNs in the context of the Internet of Things (IoT). WSNs have various purposes. Some detect various environmental and physical phenomena (such as pressure, sound, and temperature) and transmit collected data to central processing hubs. These networks consist of distributed sensor nodes with limited processing and power capabilities, communicating via short-range radio links. While WSNs have extended lifespans ranging from a few years to several centuries, providing them with sustained energy remains a challenge. Although wireless sensor applications consume minimal power during quiescent states, bursts of power are required for data transmission. The EH system emerges as an active solution, aiming to harness diverse energy sources from the environment such as vibration, solar radiation, and electromagnetic fields to generate electrical energy. By doing so, EH contributes to the longevity and efficiency of WSNs, addressing their energy needs effectively.

II Sources of Ambient Energy and Harvesting Methods

Mechanical Vibration Harvesting

Mechanical Vibration Harvesting can be done in three ways. Electromagnetic transduction exploits the movement of a magnet and/or a coil, which induces an electric current. Electrostatic transduction is based on the two plates of a variable capacitor moving, generating a change in capacitance and therefore also alternating current (AC) electricity. Piezoelectric materials can also be used to convert the mechanical motion of vibration to AC, because when mechanical strain is applied to them, they generate an electrical voltage. There are several applications for mechanical vibration harvesting, including industrial machines or ways of transportation, like streets or railway tracks. But because it requires resonant frequency matching, which is hard for small devices, because the smaller the device, the higher the resonant frequency, contains moving parts, and only generation of AC is possible, while most of the devices in a WSN need direct current (DC), mechanical vibration harvesting devices should only be used as auxiliary power supplies.

Thermal Energy Harvesting

Heat is produced as a by-product by many systems but hardly ever reused as an energy source. This is where thermal EH comes into play, exploiting either the Seebeck effect as thermoelectric harvesters, or the pyroelectric effect as pyroelectric generators. The Seebeck effect explains the phenomenon that when two specific materials are connected and a temperature gradient exists between them, a DC voltage is generated proportional to this gradient. Therefore, thermoelectric harvesters are used when a constant and high spatial thermal gradient exists. The pyroelectric effect occurs in some dielectric materials, which change their polarization when the temperature changes. This means, pyroelectric generators need, in contrast to thermoelectric harvesters, a cyclic change in temperature to reliably generate AC. For both technologies a low conversion efficiency from temperature to electricity is the major problem.

Photovoltaic Energy Harvesting

Photovoltaic is a mature technology, already used as energy supply for many different systems. The conversion of light waves into electricity is done using the photovoltaic effect, where a DC voltage is generated when semiconductors are exposed to light. In outdoor WSN this method can only be used in combination with an energy storage, as sunlight is not available all the time, while for all the time brightly lit indoor environments this could be a good energy source, even without storage.

Fluid Flow Energy Harvesting

Wind or waterflow has also been used as an energy source for decades already. Turbines convert the flow of the medium to electricity, exploiting the principle of electromagnetic induction. In WSNs we are facing the problem that turbines from other application fields cannot be used, because their form factor is too big. Here, different approaches, like oscillating wings, piezoelectric methods, or miniature turbines must be used.

Magnetic Energy Harvesting

Power delivery infrastructure exists all around the world and low amplitude magnetic fields arise from those current-carrying wires. Traditional methods are not efficient enough to use these fields as an energy source. Because of that, new approaches were found using magneto-electric (ME) composite materials, which generate an electrical charge when a magnetic field is applied.

Radio Frequency Energy Harvesting

In urban areas, radio frequency (RF) technologies are omnipresent and can be also used as energy supply. The energy of radio waves can be converted to AC or DC voltage, with a rather high efficiency between 50% and 75%, gaining power in the range of micro to milliwatts. As the energy of radio waves decreases drastically with distance, also dedicated sources can be deployed to provide an energy supply to specific devices when the distance from the ambient sources is too far, or these don’t even exist like in unpopulated areas. In WSNs especially the fact that potentially the same antenna already used for data transmission can be used to harvest energy is beneficial. Also, it has a more consistent and ubiquitous presence than many other forms of ambient energy, at least in urban areas.

III Energy Storage Consideration

An EH system should act as a buffer between variable power consumption and the dynamic range of ambient energy sources. To be self-sustainable, these systems need an energy storage mechanism to store captured energy when available and use it during periods of energy absence. While using harvested energy directly without storage can enhance longevity by reducing parts, it restricts perpetual operation to times when energy is available, which is unsuitable for many applications. Therefore, supercapacitors and rechargeable batteries are commonly used for expanding the operational capacity of wireless sensor nodes.

Batteries and Rechargeable Batteries

Primary (Non-Rechargeable) Batteries

Primary batteries offer high capacity and temperature stability but require periodic maintenance and replacement. Their energy density typically ranges from 1200 to 3780 J/cm^3, depending on the internal chemistry. These batteries allow for predictable lifetime and maintenance schedules but have a fixed capacity that limits operational time. Natural current leakage further reduces their lifespan, leading to higher long-term costs, especially in remote or hard-to-access locations such as medical, environmental, or structural monitoring domains.

Long-Term Cost and Maintenance: Using disposable batteries increases long-term costs due to frequent replacements and maintenance, particularly in remote or hard-to-access areas.

Secondary (Rechargeable) Batteries

These batteries can be recharged, reducing the need for frequent replacements. They have an energy density between 650 and 1080 J/cm^3. Despite their advantages, they are limited by their cycling capacity and will eventually require replacement as their capacity diminishes.

Rechargeable Battery Characteristics

Battery performance is influenced by its internal chemistry, affecting energy density, internal resistance, depth of discharge, self-discharge, and tolerance to overcharging. The specific energy (Wh/kg) indicates the maximum energy density, varying across different chemistries. Battery capacity refers to the total energy stored at full charge, with a typical lifetime spanning hundreds to thousands of charge/discharge cycles, during which capacity decreases due to chemical corrosion of electrodes.

Impact of Charging/Discharging

Frequent incomplete charge/discharge cycles can damage battery capacity. Specialized power management techniques can mitigate this by performing periodic complete cycles. Ambient operating temperature also affects battery longevity, with optimal performance around 20°C. Deviations from this temperature can lead to shorter battery life and more frequent charges.

Battery Types

Lead-Acid batteries are low cost and reliable but have low cycling capacity and poor performance in extreme conditions. Nickel-Cadmium (NiCd) batteries offer a long lifetime and fast charging but have low capacity. Nickel-Metal Hydride (NiMH) batteries provide better capacity and are less toxic. Lithium-Ion batteries have high efficiency, power density, and cell voltage but are costly and prone to fire when exposed to moisture. Alkaline MnO_2 batteries have the lowest self-discharge rate.

Capacitors and Supercapacitors

Conventional Capacitors

Capacitors and supercapacitors have even lower energy densities, ranging from 1-3 J/cm^3 and 10-100 J/cm^3, respectively. Conventional capacitors have long lifetimes, high power density, and fast charging/discharging rates but low energy density compared to batteries.

Supercapacitors

Supercapacitors, with properties between rechargeable batteries and conventional capacitors, can quickly accommodate large energy amounts. They offer long life cycles, high charging/discharging efficiency, and better environmental sustainability but have lower energy density and higher self-discharge rates. These attributes make supercapacitors suitable for EH sensor nodes.

Supercapacitor Types

Supercapacitors are categorized into Electric Double-Layer Capacitors (EDLC), Pseudo-Supercapacitors, and Hybrid Supercapacitors. EDLCs are the most common and cost-effective, offering good durability and cycling stability. Pseudo-Supercapacitors have higher energy density but lower power density and cycling stability. Hybrid Supercapacitors combine elements of both, providing high energy and power densities.

Comparing Rechargeable Batteries and Supercapacitors

Rechargeable batteries and supercapacitors are both widely used in WSNs. Supercapacitors generally offer longer cycle lives and higher charging/discharging efficiency but have higher self-discharge rates and lower energy densities compared to rechargeable batteries. The choice between them depends on the specific application requirements and the properties of the materials used.

IV. ENERGY HARVESTING ARCHITECTURES

Combining EH and energy storage techniques into an effective power supply system involves identifying suitable energy sources and optimizing the use of appropriate harvesting methods and storage mediums.

System Topologies

Autonomous Harvesting Systems

These systems rely entirely on ambient energy sources without using batteries, operating only when energy is available. They follow the energy neutrality principle, ensuring they never consume more energy than harvested. Prediction algorithms are employed to estimate future energy availability for effective resource management. The main advantage is simplicity and avoidance of storage-related issues, but the downside is the inability to operate without an energy source, making it suitable for on-demand applications.

Autonomous Hybrid Harvesting Systems

These systems incorporate an energy reservoir, such as a rechargeable battery or supercapacitor, allowing the harvesting device to collect energy for immediate use and storage. This common EH system type balances production and consumption rates over time, enabling perpetual operation and significantly extending system life.

Battery-Supplemented Harvesting Systems

In these systems, the battery is the primary energy source, with the harvesting device playing a secondary role. The aim is to reduce battery usage and extend system lifetime by minimizing the need for external recharging or battery replacement. These systems can operate as long as the battery has charge, making them reliable but still dependent on battery replacement over time.

Necessity for Rechargeable Storage Mediums

For applications requiring sustained high power, rechargeable batteries or capacitors combined with ambient EH mechanisms are essential. This reduces maintenance needs and enhances the efficiency and sustainability of WSNs.

Multi-Storage Systems

Single-path architectures, where harvested energy directly charges a single storage device, face the issue of 'cold booting' when the storage unit is empty. Dual-path architectures solve this by using two storage units: a primary storage device with a small capacity for quick charging and activation, and a secondary storage device with a larger capacity for long-term operation during energy shortages. This setup ensures continuous operation and reliable performance.

Dynamic Capacitor Switching (DCS)

DCS improves efficiency by dynamically switching between capacitors of different sizes based on energy availability, using an adaptive learning algorithm. This method increases the amount of energy harvested and improves sensor coverage compared to fixed capacitor approaches.

Multi-Source Energy Harvesting

Using multiple ambient energy sources concurrently enhances system reliability by reducing dependence on a single energy source. Modular plug-in EH systems with commercial off-the-shelf (COTS) components can support multiple sources, such as solar and wind, in a dual-path architecture. Examples include:

Modular EH systems combining solar and wind generators with supercapacitors and rechargeable batteries.

Multi-source harvesters using solar, wind, and water flow for near-perpetual operation in agricultural WSNs.

Systems integrating photovoltaic, thermoelectric, and piezoelectric generators for structural health monitoring of industrial machinery.

Combining different EH mechanisms can be complex and costly due to increased components and system complexity. However, it can significantly enhance energy availability and system sustainability if the operating environment justifies the added complexity.

V. FURTHER DESIGN CONSIDERATIONS

The design of efficient EH WSNs extends beyond the selection of suitable EH and storage technologies. Numerous other factors contribute to overall system efficiency, determining whether an approach is feasible.

Methodical Design Procedure

Prauzek et al. identified a methodical procedure for designing efficient EH WSNs, which includes consideration of technical items at both node and network levels, across hardware and software.

Communication Requirements

The choice of hardware components dictates a device's effective range and power consumption. In RF harvesting, the decision between single or dual antenna models impacts device complexity and form. Communication requirements must be carefully analysed in terms of data transfer, protocol, and frequency, as communication is often the most energy-intensive task for a WSN.

Control Algorithm Design

Optimizations at node and network levels are crucial for efficiency. These include:

Prediction Techniques: Balancing device operation between stored energy use and future energy expectations.

Node-Level Adaptive Control: Techniques like Maximum Power Point Tracking (MPPT) for variable energy sources.

Parameter Optimization: Enhancing system performance by fine-tuning operational parameters.

Data Compression: Reducing storage and communication overheads.

Task Distribution: Minimizing energy use by separating computational duties between node and cloud.

Resource Allocation: Optimal allocation of resources at both node and sink levels.

Node Location Optimization: Strategically placing nodes and associated network/EH infrastructure.

Regulatory Compliance: Ensuring safety while delivering optimal performance.

Task Scheduling and Interleaving

Tasks at the node level should be interleaved and scheduled to achieve robust performance and minimize energy consumption. Light tasks like sensing and computation should be frequent, while energy-intensive tasks like communication should occur less frequently. Efficient control algorithms should combine these tasks to exploit energy storage architecture effectively.

VI. Conclusion

This paper explored various contemporary EH methods for WSNs, including vibrational, thermal, solar, flow-based, magnetic, and radiofrequency methods. It also discussed the use of rechargeable batteries and supercapacitors as energy storage technologies, highlighting their characteristics, advantages, and disadvantages. The paper also examined EH system topologies, including autonomous, autonomous-hybrid, and battery-supplemented systems, and emphasized the importance of communication requirements, hardware selection, control algorithms, and task scheduling in designing efficient EH systems.

Designing EH systems for WSNs is complex but offers significant logistical, environmental, and economic benefits, especially as we move towards Industry 4.0. The appropriate EH system depends on the specific application and environment, requiring careful consideration of energy sources and various other factors for successful implementation.