State of the Art
Optimal scheduling for energy-harvesting batteryless sensory systems

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Contents

1 Introduction

This document explores the integration of sustainability in Internet of Things (IoT) devices, focusing on battery-free operations and intermittent energy harvesting. It serves as a comprehensive overview of optimizing scheduling for such systems, motivated by environmental concerns and the goal of utilizing resources more sustainably.

The discussion begins with an introduction to sustainability's significance in Internet of Things (IoT) and its role as a transformative agent. It then delves into key concepts like Energy Harvesting, Energy Efficiency, and Energy Resilience, emphasizing the ethical use of renewable energy sources.

Subsequent sections address the primary challenges, their current solutions, and inherent limitations, aiming to provide a holistic understanding of the field's state.

The document also considers secondary challenges to offer a complete view of sustainability issues in Internet of Things (IoT).

Finally, it identifies existing research gaps and proposes directions for future inquiries, concluding with the methodologies employed in compiling this State of the Art review.

2 Context

The synthesis of insights from the Intergovernmental Panel on Climate Change (IPCC)'s 2023 report[[1]] and the United Nations (UN)' "The Sustainable Development Goals (SDGs) Report 2023"[[2]] offers a comprehensive view on the multifaceted approach required to address climate change. These documents underscore the importance of sustainability, Energy Efficiency, and Energy Resilience within the realms of Internet of Things (IoT) and Energy Harvesting (EH). Together, they pave the way toward a sustainable, efficient, and resilient energy future, highlighting the interplay between these factors in global efforts to mitigate climate change impacts.

2.1 Overview

The IPCC's 2023 report[[1]], alongside the UN's 2023 SDGs report[[2]], underscores the urgent need for comprehensive strategies to combat the far-reaching effects of climate change. These reports emphasize the importance of sustainable development pathways, integrating inclusive governance, diverse knowledge, and innovative solutions to ensure resilient societies and ecosystems.

2.2 Sustainability

Sustainability, as detailed within EH and Internet of Things (IoT) applications and outlined by the UN's sustainability goals, involves a balanced approach to environmental integrity, social equity, and economic viability[Fig 1: The Sustainability Triangle1]. These technologies offer opportunities to reduce environmental impacts, enhance social inclusion, and foster economic growth through innovative solutions that minimize resource use and improve energy access.

- **Environmental** Aspect: Emphasizes renewable energy sources and energy-efficient designs to reduce carbon footprints and environmental degradation.
- **Social** Aspect: Focuses on enhancing accessibility, safety, and community well-being through equitable energy solutions and stakeholder engagement.
- **Economic** Aspect: Highlights cost savings and economic growth potential through innovative energy solutions and market creation.

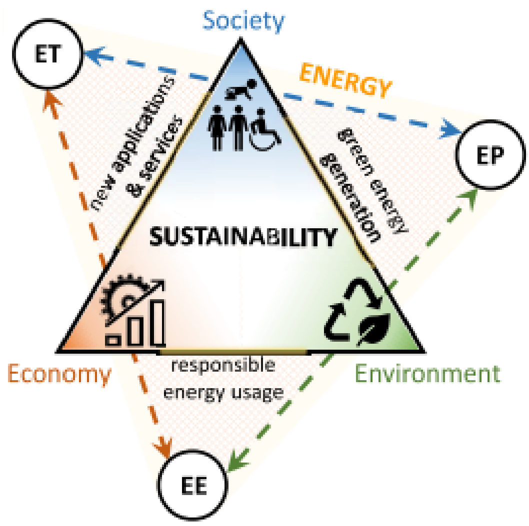

Figure 1: The Sustainability Triangle, highlighting the critical balance between environmental, social, and economic factors in achieving sustainable outcomes[3].

2.3 Energy Efficiency

Energy Efficiency is pivotal in reducing energy consumption and emissions. Internet of Things (IoT) devices enhance energy management across various sectors by enabling smart controls and predictive maintenance, while EH technologies provide a sustainable energy supply by converting ambient energy into usable power.

- **Internet of Things (IoT)**: Enhances real-time energy monitoring and management, leading to significant energy savings and reduced waste[4].
- **EH**: Offers a renewable energy source, reducing reliance on traditional energy systems and enhancing device longevity[5].

2.4 Energy Resilience

In the face of climate-induced disruptions, Energy Resilience is increasingly critical. It involves the capacity of energy systems to withstand, adapt to, and recover from disturbances, ensuring stable and reliable energy supply[6].

- **Internet of Things (IoT) for Resilience**: Employs real-time data and predictive analytics to enhance system responsiveness and recovery, contributing to a more distributed and less vulnerable energy infrastructure[7].
- **Energy Harvesting for Resilience**: Diversifies energy sources and enables autonomous operation, particularly beneficial in remote or disaster-prone areas, thus strengthening system robustness[8].

The interconnectedness of Sustainability, Energy Efficiency, and Energy Resilience, underpinned by Internet of Things (IoT), Micro-Electromechanical Systems (MEMS) and EH technologies, forms a cornerstone in the global response to climate change. Embracing these innovative approaches, as highlighted by the IPCC and the UN's SDG reports, charts a path towards a sustainable, efficient, and resilient energy landscape. The collective pursuit of these objectives, in line with the urgent and inclusive climate action called for by these reports, is essential in mitigating climate impacts and securing a livable future for all.

Following the outlined context, we will delve into specific applications and the corresponding energy sources in the subsequent section.

2.5 Applications

Below, we detail primary energy sources and their applications, as highlighted in [9] on page 8:

- **Motion** ([10]): This method encompasses Electrostatic, Piezoelectric, Electromagnetic, and MagnetoRestrictive processes for powering IoT devices through movement. Its applications range from industrial uses, such as power transformers, to consumer technologies like battery-less gaming devices[7], vibration sensor in nuclear reactor[6], to monitor and avert environmental radiation discharge.

- **Solar**: Utilizing light, Photovoltaic cells—both indoor and outdoor capable—serve as a versatile, renewable energy source crucial for infrastructure dependent on lighting schedules.

- **Thermal**: Exploiting temperature differentials allows for electricity generation useful in aerospace, automotive sensor enhancement, and wireless temperature management in food and pipelines, and for safety applications[6].

- **Magnetic Field of Electric Power Lines**: Enhances electrical efficiency and transmission by harnessing naturally occurring magnetic fields.

- **Radio Frequency**: Key to Radio-frequency identification (RFiD) technology, offering a sustainable alternative to standby modes in devices, conserving energy, and enabling early defect detection in maintenance.

- **Wind**: Facilitates environmental control in buildings through airflow energy harvesting.

Additionally, beyond the succinct explanations provided for each energy source, numerous sectors will benefit significantly:

- **Healthcare**: Biometric wearables, harnessing motion energy, facilitate continuous health monitoring without battery dependence.

- **Maintenance Operations**: Energy sources across various sectors predict maintenance needs, adapt operations, and optimize consumption.

- **Military Operations**: TerraSwarm including Smart Dust.

These innovations not only enhance Energy Efficiency (EE) but also contribute significantly toward our sustainability goals.

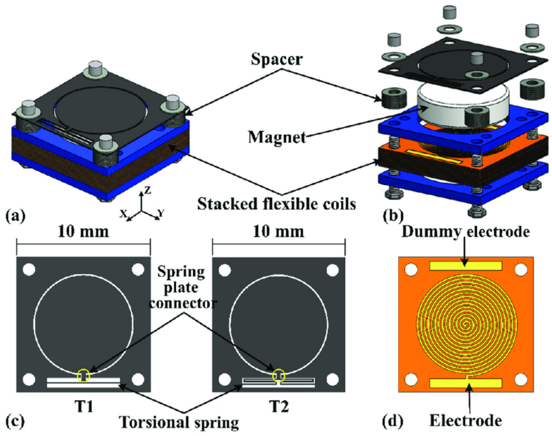

Figure 2: Schematic and exploded illustration of the assembled EVEH. (a) schematic illustration the EVEH device; (b) exploded view of the EVEH device; (c) two types of torsional spring; (d) layer of flexible coils[10].

3 Primary Challenges

In this section, we will highlight the challenges associated with the sustainability of EH batteryless MEMS and Internet of Things (IoT) devices.

3.1 Dynamic Power Management

DPM is crucial in the realm of ultra-low power IoT devices, focusing on optimizing device performance to align with workload demands, thereby reducing unnecessary power usage and enhancing energy efficiency. This strategy is increasingly important as the adoption of mobile and battery-dependent IoT devices grows, alongside the need for energy-saving operations in data centers and cloud computing. Efficient DPM practices[11] are key to meeting these challenges, emphasizing the significance of energy management in advancing the sustainability and effectiveness of IoT technologies.

The challenge of DPM lies in developing algorithms and techniques that can dynamically adjust the power states of computing devices in response to changing workload demands, resource availability, and system conditions. Several factors contribute to the complexity of DPM, including heterogeneous workloads, real-time constraints, and uncertain workload patterns[12].

Efficient DPM strategies play a crucial role in improving energy efficiency, extending battery life, reducing operating costs, and minimizing environmental impact in computing systems. However, existing approaches to DPM often suffer from limitations such as overhead and complexity, sensitivity to workload variability, and trade-offs between energy and performance.

Future research directions in DPM include:

- The development of Adaptive Algorithms (e.g.: REHASH),
- The Self-Learning Algorithms,
- Integration of Machine Learning (ML) [13], and
- Exploration of novel hardware architectures.

Addressing the challenge of DPM requires interdisciplinary research efforts spanning computer science, electrical engineering, and materials science, with the potential to drive innovation and reshape the future of computing technology.

3.2 Low-Power Hardware Design

In the realm of batteryless systems, Low-Power Hardware Design plays a pivotal role in enabling energy-efficient operation without reliance on traditional power sources like batteries. This approach focuses on crafting hardware components, such as processors, memory modules, and sensors, that consume minimal power while delivering optimal performance. This is crucial for extending the lifespan and enhancing the efficiency of batteryless Internet of Things (IoT) devices[14].

Low-Power Hardware Design in batteryless systems entails the development of components capable of operating efficiently in energy-constrained environments. This involves minimizing the average power consumption during operation and standby modes, as well as ensuring compatibility with EH mechanisms to utilize ambient energy sources effectively.

Despite advancements, Low-Power Hardware Design in batteryless systems presents several challenges. One of the primary hurdles is achieving a balance between power efficiency and performance. Ensuring high performance while operating within strict power constraints necessitates innovative design approaches and meticulous optimization.

The complexity of Low-Power Hardware Design for batteryless systems stems from various factors:

- **Energy Constraints**: Devices, especially those reliant on battery or ambient energy, have limited power resources. This necessitates hardware that can operate efficiently under such constraints.

- **Technological Limitations**: Existing hardware components are often designed for performance, with less emphasis on energy efficiency. Redesigning them for low power consumption without sacrificing performance is challenging.

- **Integration Issues**: Combining low-power components with traditional energy sources and ensuring they work seamlessly with other parts of the system can be complex.

- **Heat Generation**: High-power consumption leads to heat generation, which can damage components and affect device reliability and lifespan.

To address the challenges of Low-Power Hardware Design in batteryless systems, researchers and engineers have developed several strategies:

- **Ultra-Low-Power Components**: Development of components that utilize minimal energy for operation. This includes low-power processors, memory, and sensors.

- **Energy-Efficient Architectures**: Designing system architectures that minimize energy waste, including power gating and energy-efficient communication protocols.

- **Adaptive Power Management**: Implementing dynamic power management techniques that adjust the energy consumption based on workload, thereby optimizing the power use in real-time.

- **Use of Advanced Materials**: Exploring new materials and manufacturing techniques that can reduce energy consumption and remove toxic component[15], such as using silicon on insulator (SOI) technology or carbon nanotubes.

Despite progress, Low-Power Hardware Design in batteryless systems still faces limitations:

- **Performance Trade-offs**: Achieving ultra-low power consumption often requires sacrificing some level of performance, which may not be acceptable for all applications.

- **Complexity and Cost**: Designing and manufacturing low-power hardware components can be more complex and costly than traditional components, potentially limiting their adoption.

- **Technological Barriers**: There are physical and technological limits to how much power efficiency can be improved, especially with current materials and technologies.

- **Compatibility and Integration Challenges**: Ensuring that low-power components integrate seamlessly with existing systems and technologies without compromising functionality can be difficult.

Low-Power Hardware Design is a multifaceted challenge with significant implications for the future of sustainable and energy-efficient electronics. While the responses to this challenge have been innovative and impactful, they come with inherent limitations that require ongoing research and development. Overcoming these limitations necessitates a holistic approach, incorporating advances in materials science, electrical engineering, and computer science to pave the way for the next generation of low-power devices.

3.3 Energy-Aware Software Design

Energy-Aware Software Design is a critical aspect of modern computing, focusing on the development of software systems and applications that prioritize energy efficiency alongside performance and functionality. This approach aims to minimize energy consumption during software execution, thereby extending battery life, reducing energy costs, and mitigating environmental impact.

This encompasses the creation of algorithms, programming methodologies, and software architectures that optimize energy usage limit the sacrificing performance or user experience. It involves identifying energy-intensive tasks, optimizing resource utilization, and leveraging energy-saving techniques to maximize efficiency across various computing platforms[16], [17].

Despite its importance, energy-aware software design poses several challenges. One of the primary obstacles is achieving a balance between energy efficiency and performance. Ensuring that software operates with minimal energy consumption while meeting performance requirements requires careful consideration of algorithmic complexity, resource utilization, and system dynamics[18].

The complexity of energy-aware software design arises from various factors:

- Diverse application domains: Software applications span a wide range of domains, each with unique energy requirements and constraints, making it challenging to develop generic energy-saving strategies.
- Heterogeneous hardware platforms: Software must run on diverse hardware architectures, including mobile devices, embedded systems, and cloud servers, each with different power characteristics and optimization opportunities.
- Dynamic workload patterns: Workload characteristics may vary dynamically, necessitating adaptive software designs capable of adjusting energy usage in real-time based on workload demands and system conditions.

To address the challenges of energy-aware software design, researchers and practitioners have developed several strategies:

- Energy-efficient algorithms: Designing algorithms optimized for low energy consumption without compromising computational performance or accuracy.
- Energy Aware programming models: Developing programming models and frameworks that abstract hardware details and provide Power Aware abstractions to application developers.
- Dynamic energy management techniques: Implementing runtime systems and middleware that monitor system energy usage and dynamically adjust software behavior to optimize energy efficiency.

Despite advancements, energy-aware software design faces limitations:

- Trade-offs between energy and performance: Optimizing for energy efficiency may result in performance degradation or increased execution time, impacting user experience and application responsiveness[19].

- Complexity and overhead: Implementing energy-aware techniques may introduce additional complexity and computational overhead, potentially negating energy savings achieved by the software.
- Compatibility and portability: Energy-aware software designs may not always be compatible with existing systems or easily portable across different hardware platforms, hindering adoption and interoperability[16].

The energy-aware software design is essential for building sustainable computing systems and applications. Overcoming the challenges and limitations through continued research, innovation, and interdisciplinary collaboration is crucial for realizing the full potential of energy-efficient software design and driving advancements in computing technology.

3.4 Energy Harvesting Integration

EH integration is a vital aspect of modern electronics, focusing on the seamless incorporation of EH mechanisms into electronic systems to enable self-powered operation. This approach aims to utilize ambient energy sources, such as solar, kinetic, or thermal energy, to generate electricity for powering electronic devices and systems without the need for external power sources.

This involves the design and implementation of electronic systems and components capable of efficiently harvesting, storing, and managing energy from ambient sources. It encompasses the integration of EH modules, power management circuits, and energy storage elements into electronic devices, enabling them to operate autonomously and sustainably in various environments[19].

Despite its potential benefits, EH integration presents several challenges. One of the primary obstacles is maximizing energy extraction efficiency while ensuring compatibility with the target application's power requirements. Achieving optimal EH performance across different environmental conditions and device configurations requires careful system design and optimization.

The complexity of EH integration arises from various factors:

- Variability of ambient energy sources: Ambient energy sources, such as solar radiation or mechanical vibrations, exhibit variability in intensity, duration, and availability, posing challenges for consistent EH.
- Energy storage and management: Efficiently storing and managing harvested energy requires sophisticated power management techniques and energy storage technologies capable of handling fluctuating energy inputs and varying power demands.

- Integration with existing systems: Retrofitting EH capabilities into existing electronic systems or integrating them into new designs without compromising functionality or performance presents integration challenges.

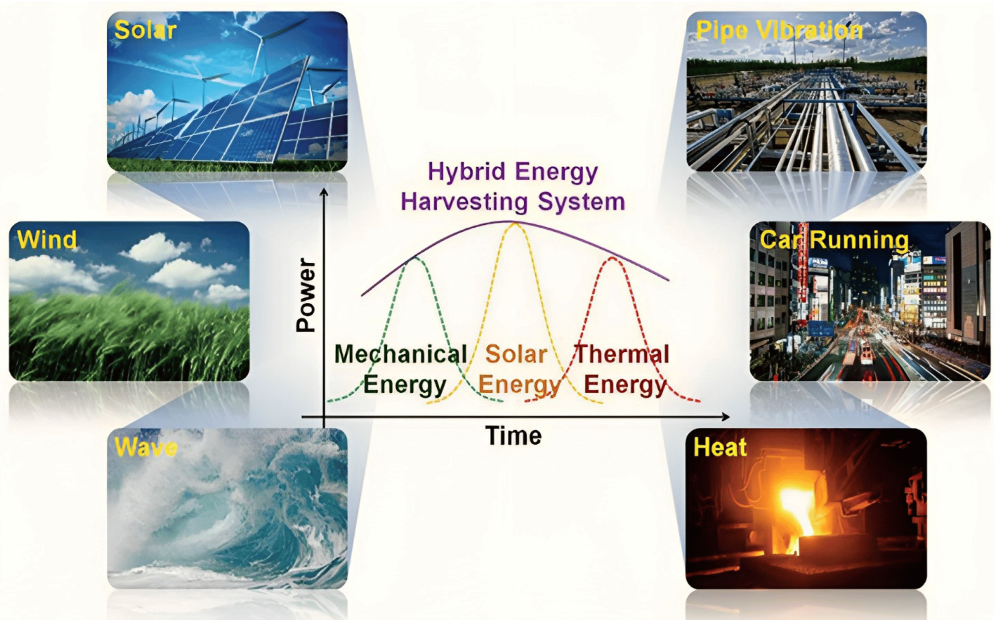

Figure 3: Diagram of a hybrid energy harvesting that uses both artificial and natural energies. [20], Page 3.

To address the challenges of EH integration, researchers and engineers have developed several strategies:

- Adaptive EH systems: Designing EH systems equipped with adaptive algorithms and control mechanisms that optimize EH performance based on environmental conditions and power requirements.

- Hybrid EH approaches (figure 3, [20]): Combining multiple EH techniques, such as solar, kinetic, and thermal harvesting, to increase energy diversity and reliability and mitigate the limitations of individual harvesting methods.

- System-level optimization: Optimizing the overall system architecture, including EH modules, power management circuits, and energy storage components, to maximize energy efficiency and system robustness.

In summary, EH integration holds great promise for enabling self-powered electronic systems and reducing reliance on external power sources. Overcoming the challenges and limitations through continued research, innovation, and collaboration is essential for realizing the full potential of EH integration and driving advancements in sustainable electronics.

3.5 Adapting to Intermittent Energy Supply

In the context of Internet of Things (IoT), batteryless, and ultra-low power technologies, Intermittent Energy Supply refers to the challenge of ensuring continuous operation under conditions of fluctuating energy availability. This is particularly relevant for IoT devices deployed in remote or energy-constrained environments, where energy sources such as solar, ambient RF, or thermal gradients are subject to variability. The key is to harness these intermittent energy sources efficiently to power devices that require minimal energy for operation[7], [16].

The adaptation involves developing energy harvesting technologies and ultra-low power circuits that can operate in environments with highly variable energy inputs. Unlike traditional systems that rely on consistent power sources, IoT and ultra-low power devices must be designed to function effectively even with sporadic energy availability, leveraging the smallest amounts of energy for maximum utility[19].

The primary challenge in this domain is designing systems that are resilient to energy fluctuations, ensuring that IoT devices can maintain functionality without constant power supply. This includes optimizing energy storage, utilizing innovative batteryless technologies, and implementing power management strategies that adjust device operations based on available energy.

The complexity of adapting to Intermittent Energy Supply in IoT and ultra-low power systems involves several factors:

- Energy harvesting efficiency: Developing technologies capable of converting ambient energy sources into usable power with high efficiency, even under varying environmental conditions.
- Power management: Designing advanced power management circuits that minimize energy consumption and dynamically adjust device operations based on the current energy availability.
- Batteryless and energy storage solutions: Exploring innovative batteryless technologies and ultra-low power energy storage solutions that can provide reliable power supply despite intermittent energy generation.

To address these challenges, various strategies have been developed:

- Adaptive energy harvesting: Implementing adaptive energy harvesting techniques that can optimize energy conversion from available sources in real-time, ensuring maximum power extraction.
- Ultra-low power design: Designing IoT devices and components that operate with minimal power consumption, extending operational life and reducing the need for frequent energy replenishment.

- Intelligent power management: Utilizing smart power management algorithms that dynamically balance energy harvesting, storage, and consumption to maintain continuous device operation.

Despite advancements, adapting to Intermittent Energy Supply in the context of IoT, batteryless, and ultra-low power technologies poses several limitations:

- Operational constraints under low energy conditions: Ensuring reliable device functionality when energy availability is minimal remains a challenge.
- Energy storage and conversion efficiency: Improving the efficiency of energy storage and conversion mechanisms is critical for maximizing the utility of harvested energy.
- Integration and scalability: Integrating these technologies into a wide range of devices and applications, and scaling them to meet diverse operational requirements, presents ongoing challenges.

Addressing the challenges of Intermittent Energy Supply in IoT, batteryless, and ultra-low power contexts requires innovative approaches that combine technological advancements, design optimization, and strategic power management. Overcoming these challenges is crucial for expanding the deployment of IoT devices in energy-constrained environments, paving the way for a more connected, efficient, and sustainable world.

3.6 Sensor Optimization

Sensor optimization is a critical aspect of sensor design and deployment, focusing on enhancing the performance, efficiency, and reliability of sensors in various applications. This involves optimizing sensor parameters, configurations, and algorithms to achieve accurate and timely data acquisition while minimizing energy consumption and resource utilization.

Sensor optimization encompasses a range of techniques and strategies aimed at improving the effectiveness and efficiency of sensors. This includes optimizing sensor placement, calibration, sampling rates, and signal processing algorithms to maximize the quality and utility of sensor data while minimizing power consumption, latency, and cost[14], [19].

The primary challenge of sensor optimization lies in achieving a balance between sensor performance and resource constraints. Designing sensors that deliver accurate and timely data while operating within limited power, memory, and processing resources requires careful optimization and trade-offs.

The complexity of sensor optimization arises from various factors:

- Resource constraints: Sensors deployed in resource-constrained environments, such as Internet of Things (IoT) devices or wireless sensor networks, must operate within strict limitations on power consumption, memory usage, and processing capabilities.
- Environmental variability: Environmental factors such as temperature, humidity, and interference can affect sensor performance and reliability, necessitating robust optimization techniques to mitigate their impact.
- Application-specific requirements: Sensors deployed in different applications, such as environmental monitoring, healthcare, or industrial automation, have unique requirements and constraints that must be considered during optimization.

To address the challenges of sensor optimization, various strategies have been developed:

- Energy-efficient sensor design: Designing sensors with low-power components, optimized circuitry, and energy-efficient communication protocols to minimize power consumption and extend battery life.
- Adaptive sensing algorithms: Developing adaptive sensing algorithms that dynamically adjust sensor parameters and sampling rates based on environmental conditions, user requirements, and energy availability to optimize performance and efficiency.
- Distributed sensor networks: Deploying distributed sensor networks with decentralized processing and collaborative sensing capabilities to distribute computation and reduce energy consumption.

Despite advancements, sensor optimization poses several limitations:

- Trade-offs between performance and resource consumption: Optimizing sensor performance may require increased power consumption, memory usage, or processing resources, leading to trade-offs that impact overall system efficiency and scalability.
- Sensing accuracy and reliability: Optimized sensor configurations and algorithms may sacrifice accuracy or reliability under certain conditions, affecting the quality and usefulness of sensor data.
- Complexity and implementation challenges: Implementing sophisticated optimization techniques and algorithms may introduce complexity and overhead, requiring specialized expertise and resources for design, development, and deployment.

The sensor optimization is essential for maximizing the effectiveness and efficiency of sensor systems in various applications. Overcoming the challenges and limitations through continued research, innovation, and collaboration is crucial for realizing the full potential of sensor technology and enabling transformative applications in fields such as Internet of Things (IoT), healthcare, environmental monitoring, and beyond.

In conclusion, addressing the sustainability of EH batteryless Internet of Things (IoT) devices requires a multifaceted approach that tackles the challenges of DPM, low-power hardware and software design, EH integration, Intermittent Energy Supply, and sensor optimization. Overcoming these challenges necessitates ongoing research, innovation, and interdisciplinary collaboration to develop solutions that are not only energy-efficient but also practical, reliable, and scalable.

4 Other Challenges

4.1 Energy-Efficient Communication Protocols

The proliferation of Internet of Things (IoT) technology underscores the necessity for energy-efficient communication protocols crucial for the sustainability and operational longevity of Internet of Things (IoT) devices, especially in power-limited applications[6].

The primary challenge stems from the inherent energy constraints of Internet of Things (IoT) devices and the need for constant data transmission.

Innovations include the development of Low-Power Wide-Area Network (LP-WAN) and advancements in protocols like Constrained Application Protocol (CoAP) and Message Queuing Telemetry Transport for Sensor Networks (MQTT-SN) designed to reduce power consumption[13].

Challenges include maintaining high data transmission reliability while minimizing energy use and standardizing protocols across the Internet of Things (IoT) ecosystem.

4.2 Environmental Adaptability

The effectiveness of Internet of Things (IoT) and energy harvesting technologies is influenced by their adaptability to environmental conditions[6].

Environmental conditions can affect the efficiency of energy harvesters and device performance.

Efforts focus on creating resilient technologies adaptable to various conditions and integrating adaptive algorithms.

Main limitations include the complexity of designing adaptable devices without increasing costs or compromising efficiency.

4.3 Fault Tolerance

The reliability of energy harvesting systems and Internet of Things (IoT) devices is critical, especially in remote or critical applications where maintenance is challenging. Fault tolerance—the ability to continue operation in the event of a component failure—is a key aspect of this reliability.

Variations in energy availability and environmental conditions can lead to unpredictable system behavior, while physical damage and component wear over time may also induce failures[5].

Techniques to enhance fault tolerance include redundancy, where critical components are duplicated to take over in case of failure, and the development of self-healing materials and circuits that can automatically repair minor damages.

Implementing fault tolerance increases the complexity and cost of devices. Moreover, there is a trade-off between the level of redundancy and the device's energy consumption and size.

4.4 Security and Privacy

As Internet of Things (IoT) devices often collect and transmit sensitive data, ensuring their security and privacy is paramount. The challenge is magnified in energy harvesting Internet of Things (IoT) devices, where resource limitations may restrict the implementation of robust security measures.

The open and distributed nature of Internet of Things (IoT) networks, along with the use of standard communication protocols, can expose devices to various security threats, including data breaches and unauthorized access.

Developing lightweight cryptographic algorithms and secure communication protocols specifically designed for Internet of Things (IoT) environments. Efforts also include the use of blockchain technology to ensure data integrity and authentication[21].

Achieving a balance between security level and energy consumption remains a significant challenge, as more sophisticated security measures typically require additional computational resources.

4.5 Lifecycle Management

The environmental impact of Internet of Things (IoT) devices, particularly those enabled by energy harvesting technologies, extends beyond their operational life. Effective lifecycle management, including recycling and end-of-life disposal, is essential for minimizing this impact.

The increasing volume of electronic waste, coupled with the hazardous materials often used in electronic components, poses a significant environmental threat[6].

Strategies include the design of devices with recyclable materials, the development of biodegradable electronic components, and the implementation of take-back programs for electronic waste.

The primary challenges are the cost and logistical complexity of recycling programs, as well as the current lack of standardization for the recyclability of Internet of Things (IoT) devices.

5 Limitations

The section effectively consolidates common limitations in the development and implementation of energy-efficient technologies and systems. It highlights five main areas: technological and economic challenges, performance trade-offs, infrastructure and policy constraints, integration challenges, and the complexity and cost of advanced techniques. Each point underscores critical barriers to scalability and adoption, pointing to the need for innovative solutions, supportive policies, and infrastructure improvements to overcome these hurdles and advance the sustainability of Internet of Things (IoT) and energy harvesting systems.

6 Potential Future Directions

How can adaptive algorithms be designed and optimized to efficiently manage energy resources in Internet of Things (IoT) devices, taking into account factors such as energy availability, process priority, storage options, and operational frequency, to ensure the successful execution of processes?

This main question can be split into several sub questions:

- **Optimization in Ultra-Low Power Contexts**: In the context of ultra-low power, IoT, and battery-less environments, what strategies are most effective for designing and optimizing adaptive algorithms?
- **Decision-Making Based on Inputs**: How can an algorithm dynamically make optimal decisions to ensure successful process execution, considering varying inputs?
- **Algorithm Impact on System Resources**: How Algorithm can be adapted to different architectures (considering processor types, frequency, number of cores, etc.)?
- **System Resources influence Algorithm**: How the system resources (processor types, frequency, number of cores, ...) are impacting the adaptive algorithm?
- **Compiler Choice and Energy Consumption**: Does the choice of compiler have an impact on optimizing energy consumption, and if so, how?
- **Methodology Abstraction for Architectural Adaptability**: How can we improve the abstraction of adaptive algorithm methodologies to be applicable across different architectures?
- **"Rebound Effect" in Optimal Scheduling Algorithms**: What is the "Rebound Effect" resulting from the implementation of optimal scheduling algorithms, and how does it affect energy consumption?

- **Comparative Impact on Device vs. Core Consumption**: How does the adoption of adaptive algorithms affect the overall device consumption compared to core consumption specifically?
- **Application of Process, Tasks, and Finite State Machines (FSM)**: In the context of adaptive algorithms, how can processes, tasks, and FSMs be utilized effectively?
- **Completeness of Energy Complexity Theory**: Is the theory of energy complexity comprehensive enough to encompass the nuances of adaptive algorithm design in IoT devices?

7 Conclusion

This State of the Art unveils the intricate layers of sustainability in IoT ecosystems, particularly emphasizing the pivotal roles of Energy Harvesting, Efficiency, and Resilience.

By methodically dissecting the spectrum of challenges—from their genesis to current mitigative strategies and inherent limitations—this document lays a comprehensive foundation for understanding sustainability's multifaceted impact on IoT. Moreover, it critically evaluates these challenges, paving the way for future research through proposed thesis questions.

These inquiries, rooted in the document's analytical insights, invite exploration beyond conventional boundaries, promising innovative solutions for a sustainable technological future.

A Methodology

Our research delves into "Optimal scheduling for energy-harvesting batteryless sensory systems" highlighting key concepts like "Energy-Harvesting," "Batteryless," and "Scheduling." Our initial broad search scope was refined by incorporating terms such as "MEMS," "IoT," "Intermittent," and "Ultra Low Power" to closely align with our objectives of promoting "Energy Efficiency" and "Green IT."

Upon selecting publications based on relevance, citation count, and recency, we conducted further analysis by exploring additional works by the same authors and cross-verifying the gathered data to ensure accuracy.

This meticulous search strategy shaped our research framework, necessitating precise searches to enrich each section of our review. We predominantly sourced information from IEEExplorer, ACM Digital Library, ResearchGate, and Google Scholar, with selective contributions from DirectScience and Springer, to compile essential insights.

Acronyms

CoAP Constrained Application Protocol. 19

EE Energy Efficiency. 7

EH Energy Harvesting. 4–6, 9, 10, 13, 14, 18

IPCC Intergovernmental Panel on Climate Change. 4, 6

LPWAN Low-Power Wide-Area Network. 19

MEMS Micro-Electromechanical Systems. 6, 9

ML Machine Learning. 9

MQTT-SN Message Queuing Telemetry Transport for Sensor Networks. 19

RFiD Radio-frequency identification. 7

SDGs Sustainable Development Goals. 4

UN United Nations. 4

Glossary

Adaptive Algorithms Algorithms that modify their operation or behavior in response to changes in their environment or input data. 9

DPM Dynamic Power Management, a strategy for optimizing the power consumption of computing devices dynamically in response to workload demands and energy availability. 9, 18

Electromagnetic It encompasses the laws and phenomena associated with the electromagnetic force, which is a fundamental interaction between particles with electric charges. The electromagnetic force is responsible for practically all the phenomena encountered in daily life (with the exception of gravity), including the technologies we use, from household appliances to understanding the structure of atoms[22].. 7

Electrostatic Electrostatic phenomena involve the interactions and forces between stationary electric charges, explained by Coulomb's law, which includes the forces that electric charges exert on each other without moving.. 7

Energy Aware Involves understanding and managing the overall energy consumption of a system over a period, focusing on achieving long-term energy efficiency and sustainability by optimizing energy usage patterns and behaviors.. 12

Energy Efficiency The goal to reduce the amount of energy required to provide products and services, by using less energy to achieve the same or an improved level of performance.. 3–6

Energy Harvesting The process of capturing energy from ambient sources and converting it into usable electrical power. 3

Energy Resilience The ability of energy systems to withstand, adapt to, and recover from disturbances while ensuring stable and reliable energy supply.[23]. 3–6

Energy-Aware Software Design Software design methodology that prioritizes energy efficiency, aiming to reduce the energy consumption of software operations. 11

EVEH The Electromagnetic Vibration Energy Harvesters, or EVEH, were proposed in the late 1900s. These transducers transform kinetic energy (vibration) into electrical energy.. 8

Finite State Machines (FSM) are computational models used to design logic in systems. They transition from one state to another based on certain inputs and a set of rules. FSMs are particularly useful in ultra-low power, batteryless IoT devices because they can efficiently manage device operations with minimal power usage. By simplifying the control logic into defined states, FSMs can help reduce the power consumed by these devices during both active and idle periods.. 22

Intermittent Energy Supply Energy supply characterized by irregular availability, common with renewable energy sources like solar and wind. 15, 16, 18

Internet of Things (IoT) concept involves devices equipped with sensor(s) that are connected to a network, enabling the digitalization of the physical world through continuous monitoring. [24]. 3–6, 9, 10, 15, 17–21, 28

Low-Power Hardware Design The design approach for creating hardware components that consume minimal power, essential for batteryless and energy-constrained devices. 9–11

MagnetoRestrictive Similar to piezoelectric materials, magnetostrictive materials change their shape or dimensions in the presence of a magnetic field. This property is utilized in various applications such as sensors and actuators, where the conversion between magnetic and mechanical energy is required. While a direct source definition was not retrieved in this search, this explanation aligns with the known scientific understanding of the term.. 7

Photovoltaic refers to the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect. This process is a method for generating electric power by using solar cells to convert energy from the sun directly into a flow of electrons by the physical and chemical phenomenon known as the photovoltaic effect.. 7

Piezoelectric It generally refers to the ability of certain materials to generate an electric charge in response to applied mechanical stress. This effect is reversible, meaning that these materials can also change shape when an electric field is applied, a phenomenon used in various applications such as sensors, actuators, and generators[25].. 7

Power Aware Refers to the system's capability to monitor and adapt its power consumption in real-time, aiming to optimize power usage and performance without compromising the operational needs of the system.. 12

Process In computing, a process is an instance of a computer program that is being executed. It contains the program code and its current activity.. 22, 28

REHASH is a framework, is a flexible heuristic-adaptation-based runtime for intermittently-powered devices.[26]. 9

Self-Learning Algorithms Algorithms capable of autonomously improving their performance over time through experience without explicit programming for all scenarios. 9

Smart Dust referes to tiny, autonomous wireless sensors that are about the size of a grain of dust. These sensors are equipped with processing, communication, and environmental sensing capabilities, such as temperature, humidity, light sensors, and more. They are designed to be deployed in the environment to monitor and collect data on various phenomena. These sensors are typically interconnected in ad hoc networks, allowing them to communicate with each other and transmit the collected data to base stations or other devices for analysis. The idea behind Smart Dust is to create a large-scale network of distributed sensors that can be used for monitoring extensive areas, such as industrial environments, urban areas, natural habitats, etc[27].. 7

Sustainability A holistic approach that considers environmental, social, and economic dimensions to meet present needs without compromising the ability of future generations to meet their own needs.[23]. 6

Tasks Tasks can be considered as smaller than Process, more specific units of work executed by the computer.. 22

TerraSwarm TerraSwarm is a research initiative that focuses on developing technologies related to smart dust and the Internet of Things (IoT). It aims to create a "swarm" of smart devices that can sense and interact with the physical world in real-time. The term "terra" in TerraSwarm represents the connection to the Earth's environment. TerraSwarm's research encompasses various areas such as system architecture, energy efficiency, security, and scalability to enable the deployment of large-scale networks of interconnected smart devices. This project is ended from the 31 December 2017[28].. 7

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