Enabling Ubiquitous and Sustainable Batteryless IoT

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Abstract

Recent advancements in low-power electronics and energy harvesters that utilize ambient sources such as solar, thermal, and RF power present significant opportunities for the sustainability of IoT devices by enabling batteryless sensor systems. However, despite these developments, several challenges hinder the widespread adoption of batteryless IoT. This study discusses solutions that effectively overcome these challenges and highlights potential future directions to enable ubiquitous and sustainable batteryless IoT systems.

CCS Concepts

• **Computer systems organization** → **Embedded software**; **Embedded hardware**.

Keywords

Batteryless embedded systems, Ubiquitous and Sustainable IoT

1 Introduction

Battery-powered IoT devices have transformed monitoring in smart cities, agriculture, and healthcare, they face sustainability challenges due to frequent battery replacements, maintenance burdens, and e-waste. Batteryless sensors that utilize ambient energy offer a sustainable and maintenance-free alternative; however, their adoption remains limited due to the requirement of specialized hardware and software that depend on environmental conditions. This paper analyzes core hardware and software challenges limiting the widespread adoption of batteryless IoT and outlines research directions to facilitate the development of ubiquitous and sustainable batteryless IoT.

2 Core Challenges Of Batteryless IoT

Batteryless devices accumulate harvested ambient energy into small storage units, but limited and unpredictable availability of ambient energy often causes frequent power failures. These failures result in the loss of volatile states, such as SRAM variables, peripheral configurations, and timer subsystems. This leads to non-termination, memory inconsistencies, and unsafe operations. Therefore, non-volatile memories such as FRAM are needed to retain the volatile state across a power failure. As a result, designing batteryless sensors poses both hardware and software challenges that demand specialized expertise.

Requires Intermittent Programming Expertise. To maintain volatile states and ensure forward progress, batteryless systems utilize intermittent programming methods such as checkpointing or a task-based model [6, 9]. However, relying on these approaches alone is insufficient. Programmers must also consider issues like non-termination bugs, peripheral consistency, and data freshness [6, 7]. These factors are influenced by hardware configurations, including energy storage size and ambient energy profiles, as they affect the frequency of power failures and charging times.

Challenges to keep track of time. Batteryless systems can fail in operations like network synchronization [1] and time-sensitive tasks [6] due to loss of local time during power failures. Capacitor-based timekeeping mitigates this by utilizing the discharge characteristic of the capacitor but suffers from low resolution, limited range, and environmental dependency [8]. Unpredictable ambient energy leads to variable charging times, resulting in unreliable timekeeping and the need for capacitor adjustments based on energy conditions.

Energy Storage and Management Complexity. Batteryless sensors use capacitors to store harvested energy, making the choice of capacitor size a key design consideration for these systems. A larger capacitor enables longer operation but slower, longer, and infrequent charging, while a smaller one charges quickly and more frequently. Additionally, some energy-hungry peripheral operations may drain the stored energy or require more energy than other operations. Therefore, the designer should consider all these factors when selecting the capacitor size and designing the system[10].

Enabling Smart Applications. The sustainability of IoT devices requires embedded intelligence in resource-constrained devices. However, frequent power failures lead to increased latency in DNN applications. Further, deploying DNN applications on batteryless devices necessitates awareness of energy consumption and time constraints [2, 5]. As a result, the combination of edge inference—already facing its own challenges—along with the issues of intermittent computing makes it difficult for these applications to gain widespread adoption in batteryless systems.

In brief, these challenges indicate that designing batteryless systems demand specialized expertise in scopes ranging from hardware design to application development, creating a barrier to their widespread adoption across general applications.

3 Toward Widespread Batteryless IoT

Environmental energy variability complicates the hardware and software design of batteryless systems. For these systems to achieve wider adoption, they need to adapt to changing conditions automatically, without requiring specific tuning, and the programming should be simplified to eliminate the need for specialized expertise. To address these challenges, we have proposed solutions outlined in Section Section 2.

Minimizing Programmer's Burden. We introduced Immortal Threads [9], which is the first intermittent computing runtime with pseudo-stackful multithreading, resolving non-termination issues via micro-continuations and allowing familiar multithreading concept without specialized intermittent programming knowledge. In addition, we presented EaseIO [6] introduces re-execution semantics to manage idempotence issues due to repeated I/O operations.

Its language interfaces let programmers specify re-execution requirements, while the compiler front end reduces the burden of the programmer by ensuring application consistency and safety. Our recent study, ARTEMIS [7], enables flexible property checking at runtime, verifies diverse constraints and specifies different corrective actions dynamically. These approaches improve adaptability to changing energy conditions while avoiding bugs like non-termination by decoupling monitoring logic from the application.

Future Directions. *While these solutions simplify programming, they still require expertise, underscoring the need to fully abstract this complexity from developers.*

Ensuring Reliable Timekeeping. Power failures are inherent in batteryless sensors, making it crucial to track the duration of these power failures for time-sensitive applications. Our ETAP [4] tool analyzes completion times based on energy conditions, but time tracking at run time is still essential. Existing capacitor-based timekeeping solutions have limited range and resolution tied to their capacitor size and ambient energy. Therefore, we focused on enhancing resolution using a capacitor bank that adapts to energy conditions in our CHRT++ [8] design, but it still has a limited measurement range due to relying on the capacitor remanence characteristic. In contrast, our SQUID [11] solution employs software-based energy monitoring for unlimited range, but it is vulnerable to rapidly changing power conditions.

Future Directions. *Reliable timekeeping still lacks solutions that combines high resolution, environment-independent, and unlimited-range.*

Efficient Energy Management. Efficient energy storage is vital in batteryless systems to utilize scarce energy effectively. Single-capacitor energy storage designs with a large capacitor ensure full energy utilization but charge slowly. In contrast, federated energy storage architectures allow for faster charging by employing dedicated small capacitors for each peripheral, although they suffer from energy fragmentation [10]. Therefore, our GRANT [10] architecture handles this by enabling energy transfer between dedicated capacitors, combining the unified capacity of single designs with the quick charging of federated models. However, energy transfer between capacitors may lead to increased energy loss. Therefore, in CapDYN [3], we designed an innovative energy storage architecture that enables fully autonomous reconfiguration of the capacitor bank energy storage. This enables faster charging, similar to a small capacitor, and longer execution times, like a large capacitor.

Future Directions. *The architectures that adapt to varying energy conditions and maximize harvested energy is still needed; adaptive capacitor banks offer a promising solution.*

Energy Efficient Inference. On-device intelligence is crucial for ubiquitous batteryless IoT, but complex computations under variable energy and limited resources demand specialized strategies. Therefore, we developed SparseComp [5] to compress selected DNN layers with minimal accuracy loss, and gNet [5] as an early exit architecture with minimal memory overhead in FreeML [5]. FreeML enable efficient DNN inference adaptable to changing energy conditions without retraining. We also introduced Fast-Inf [2], an innovative embedded intelligence solution for extremely resource-constrained, batteryless devices. It employs binary tree-based neural networks that are exceptionally fast and energy-efficient due to their logarithmic time complexity.

Future Directions. *Batteryless inference is restricted to specific microcontroller models; integrating these methods into brand-new microcontrollers will promote their adoption across various applications.*

4 Conclusion

The main obstacle to widespread adoption of batteryless sensors is the unpredictable variability of ambient energy, which forces application-specific, expert-driven design and programming. To overcome this challenge, we need general hardware and software solutions that can adapt to changing conditions without the need for customization. This would allow developers to create battery-free systems without requiring specialized expertise.

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