Conceptualizing an Architecture Description Model for Battery-less Energy Harvesting Systems

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***Abstract*—The rapid proliferation of smart devices calls for a critical need for sustainable and efficient power solutions. Traditional battery-powered systems face limitations such as finite lifespans, high maintenance costs, and substantial environmental impacts. Battery-less energy harvesting systems (BEHSs) emerge as a promising alternative, capable of capturing ambient energy of different sources to sustain device operations. However, designing BEHSs presents unique challenges. There's a necessity for tight integration between hardware and software to effectively manage the variability and intermittence of harvested energy. Unfortunately, current architectural representations for BEHSs are often informal, lacking the necessary standardization. This work seeks to conceptualize the need for a formal system model for BEHSs, such as an Architecture Description Language (ADL). It would be able to define precise interactions between subsystems and support the parallel design of hardware and software components. Future work includes defining a proper ADL with a formal graphical representation, and applying it to relevant BEHSs solutions.**

***Index Terms*—Battery-less Energy-Harvesting Systems; Internet of Things; Intermittent Computing; Architecture Description Language.**

I. Introduction

The world is witnessing an unprecedented growth of smart devices. From personal wearables that monitor health and fitness [1] [2], to automated factories [3], these devices are being deployed at an impressive scale. Driven by trends such as the *Internet of Things* (IoT), *Industry 4.0*, *Smart Cities*, and *5G networks*, the number of connected devices is expected to rise from billions to trillions in the coming years [4].

As the number of smart devices grows, so does the challenge of powering them. Many are deployed where access to mains electricity is impractical or even impossible [5]. Wired power sources are not even feasible in applications requiring mobility, such as implantable medical devices or asset tracking. Hence, the lead powering solution has remained heavily centred around batteries [6], which brings new challenges.

Devices are desired to carry on maintaining long operational lifetimes despite facing significant difficulties pertinent to battery usage, such as a need for frequent replacements, unreliable operation due to their natural limitations, and a negative impact on the environment [7]. To mitigate and avoid difficulties surrounding battery-powered devices, academic and industrial research communities have been turning to alternative strategies, such as Energy Harvesting (EH) [4].

This methodology consists of using a self-powered subsystem capable of harnessing sufficient power from ambient energy sources, such as thermal, solar, vibrations or radio-frequency (RF), and converting it into electrical energy [4] [6]. However, due to the variability and limitations of these natural sources, battery-less energy harvesting systems (BEHSs) are knowingly hard to design [4]. EH systems often provide insufficient, inconsistent power, creating significant obstacles to continuous operation.

One effective strategy for managing the complexity of BEHSs is to adopt high-level abstractions. These abstractions could provide a formal blueprint that captures the relationships between EH modules, information processing elements, and communication interfaces. This work proposes the development of an Architecture Description Language (ADL) as a possible solution.

II. Background

A. Energy Harvesting Components

A typical EH system consists of three main components: the harvesting circuit, the energy storage, and the load [8] [9].

The *energy harvesting circuit* collects energy from the environment and converts it into electrical energy [10]. Different sources like photovoltaic panels or RF radiation possess distinct characteristics and power densities [11]. The best choice of harvester will depend on the application being developed [12] [13].

Additionally, EH systems normally address the dynamic nature of energy availability by implementing *energy storage* mechanisms to capture and store surplus energy for subsequent use. Technologies differ in properties such as capacity, energy and power density, self-discharge rates and operating temperature [4] [14] [15]. The most traditional choices have been rechargeable electrochemical batteries, capacitors and supercapacitors [14] [15].

The *load* typically consists of a microcontroller unit (MCU) and several peripheral devices [16]. The MCU generally executes the application's firmware and manages the EH hardware, with any peripherals connected to them extending the system's capabilities [15], such as sensors, actuators or wireless communication modules. Lastly, a power management integrated circuit (PMIC) is normally present to manage the energy flow between the energy harvester, energy storage and the load [10] [15].

B. Energy Harvesting Architecture

An EH system as described previously can be classified according to two architectures: *harvest-use* and *harvest-store-use* [9] [17]. The first consists of energy being used as soon as it is harvested, powering the load without requiring storage elements. The second consists of using a storage mechanism to store excess energy, becoming important in deployments when the power consumption requirements of the system exceed the harvested energy output.

Moreover, EH systems suffer from unpredictable interruptions of unknown duration, so system support is usually shown through three primary solutions [18] [19]. In *energy-neutral operation*, harvested energy matches or exceeds the energy consumed, using storage to handle short-term outages. In *power-neutral operation*, power generated equals the power consumed and computing is adapted to match available power levels. Lastly, for *intermittent operation*, energy storage ceases to provide sufficient energy to the system, but the system continues operation depending on application requirements.

Finally, controlling storage capacity is crucial for BEHSs, and different buffer architectures have been developed to optimize energy storage and power flow [20], with the principal being: zero storage [21] [22], single capacitor [18] [23], capacitor banks array [24], federated capacitors [25] [26] and polymorphic capacitor array [27].

III. Proposal

A. An Architecture Description Model for BEHSs

Most BEHS solutions are focused on hardware implementations and runtime abstractions, and few seem to address the design of the system as a whole or focus on the overall system structure. This resulted in a confusing space of implementations with no way to characterize different system models, which is undesirable given the complexity of developing BEHSs [28] [29] [30]. Furthermore, modelling BEHSs presents unique challenges due to their reliance on intermittent energy sources and the critical necessity of managing energy flows effectively.

However, a well-defined Architecture Description Language (ADL), designed specifically for BEHSs, could offer the precise semantics needed to bridge the gap between these diverse implementations. ADLs are formal languages designed to describe the structure of a system [31]. They provide a systematic approach to modelling complex systems, offering representations that facilitate analysis, design and verification of these system's architectures.

Therefore, we propose developing an ADL for BEHSs that would be structured around five key principles. The first is **Separation of Power and Data Lines** as we must distinguish power and data flows. Energy routing and data communication would be modelled independently, guaranteeing the precision of energy management. Next is **Definition of Common Energy-Related Signals**, since well-defined energy-related signals help with communication about energy availability and allow users to model how energy moves through the system. Thirdly, **Definition of Base Components** to provide a modular framework and facilitate integrating individual components into the architecture. Based on the background analysis of BEHSs, our model would have four subsystems: energy harvester, energy storage, power management and computational processing. Then, we have **Definition of Interaction Mechanisms**, because we need a mechanism to distinguish data-driven and event-driven signals, to appropriately describe how components interact in real-time. Finally, we need **Graphical Representation** to offer a clear notation of the system's architecture, and detail energy flow, power distribution and interactions between subsystems.

B. Components, Interactions and Ports

Our model proposes the definition of four primary component types: **Energy Harvesting**, **Energy Storage**, **Power Circuit** and **Load**. These are the core elements present in the BEHS that are needed to operate the system under intermittent power, but the model would allow for the inclusion of additional components.

The interactions between these components ensure that energy is harvested, stored and used effectively, and we can abstract through the following concepts. **Connection Lines** represent real hardware connections and establish the energy and data links between components. We have *power lines* to model the energy flow and *data lines* to exchange information between them. Meanwhile, **Signals** represent how components communicate, transmitting crucial information about the system. We defined *command signals* to trigger specific actions, *configuration signals* to adjust system parameters dynamically and *status signals* to provide feedback about the system state. Lastly, **Ports** are interfaces through which components exchange energy and data. We have *power ports* to manage how energy is distributed in the system, *data ports* to handle data flows between components, and *event ports* to coordinate intermittent communication as the system state changes.

IV. Future Works

This paper proposed an architecture description model for battery-less energy harvesting systems (BEHSs). We listed important principles that should be used as a basis for structuring the proposed Architecture Description Language (ADL). Then, we suggested a model for this architecture in terms of components and the interactions between them, based on our surveyed background of BEHSs.

Future work would include establishing a proper ADL definition for the proposed model. We would elaborate a graphical notation for the ADL and establish more detailed definitions and rules for the suggested components and component interactions. Then, we would apply this model to existing BEHSs solutions to better understand its implementation, benefits and limitations.

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