Demo: A Flexible Extension Board for IoT Devices to Enable their Batteryless Operation

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Abstract

Research on batteryless systems has recently bloomed, allowing the creation of IoT applications where devices operate exclusively from energy harvested from the environment. However, despite recent advances, batteryless systems still suffer from a *rigid hardware design*, with a given target device coupled with a built-in harvester and predefined components, which limits flexibility. We fill this gap and introduce BPMx: an extension board to build batteryless systems offering an unprecedented level of flexibility in the choice of target device and harvester. Moreover, BPMx integrates a fully-configurable power manager with user-defined voltage thresholds, supply voltage, and the ability to fully disconnect subsystems such as a built-in real-time clock and non-volatile memory. BPMx is affordable (≈ 40 EUR), open-source, compatible with the popular Arduino Rev3 pin layout, and needs as little as 30 µA to operate. In this demo, we showcase how BPMx enables the batteryless operation of an `nRF52840-DK` implementing a periodic sensing application.

CCS Concepts

• **Hardware** → *PCB design and layout*; *Renewable energy*; • **Computer systems organization** → *Embedded hardware*.

Keywords

BPMx, Battery-free system, Energy harvesting, Hardware, Low-power design, Power management, Non-volatile memory, RTC.

1 Motivation

The Internet of Things (IoT) is revolutionizing our society by enabling greener buildings and cities, or by enhancing agricultural and industrial processes. Unfortunately, IoT devices mainly use batteries as their primary power source, which is not ideal. In fact, batteries are bulky, heavy, not sustainable, and – even if rechargeable – wear out after some time, which leads to increased maintenance effort and costs [4].

Recent studies have focused on powering IoT devices only from ambient energy extracted from their surroundings (such as solar, thermal, or kinetic energy) via so-called *energy harvesters* [2]. These harvesters typically capture small amounts of energy from the environment and store it in a (super-) capacitor until there is enough power to operate the device.

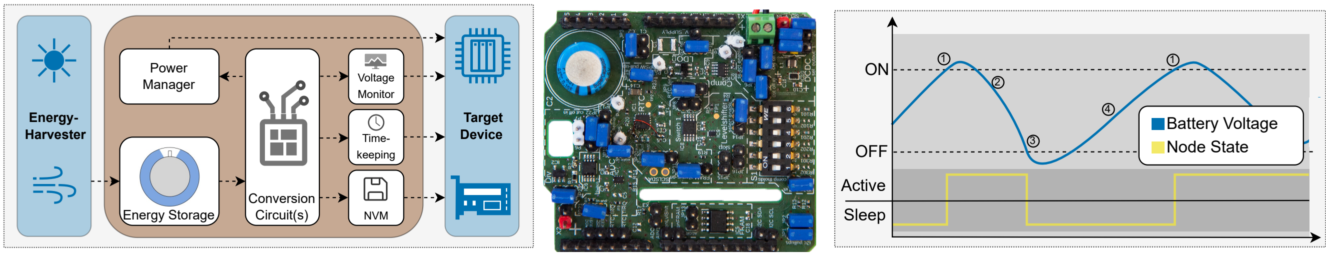
Efficiently utilizing a (super-) capacitor's charge-recharge cycle to achieve the longest possible continuous runtime and the system's ability to respond to events in a timely manner requires proper hardware support, i.e., a set of configurable components such as power management and voltage monitoring, a reliable notion of time, and non-volatile memory (NVM).

The gap to fill. We argue that the community still needs to provide an affordable and flexible extension board for IoT DevKits and SoCs, enabling the creation of batteryless systems. Such extension board would sit in between a *harvester* scavenging energy and a *target device* fulfilling a given task; and would further provide the following key components.

- *Power manager.* This module maximizes the target's runtime and avoids undefined low-voltage states by enabling or disabling the target device at specific levels of charge.
- *Voltage monitor.* Accurate response to power dropouts is essential for a batteryless system. A voltage monitor takes care of this by enabling measurements of the capacitor's current level of charge and by including an interrupt pin that triggers alerts at configurable voltage thresholds.
- *Timekeeping.* To completely turn off the target device and not lose timing information (which is essential to maintain network synchronization or to schedule long-term events), a timekeeping module is required. The latter can be based, for example, on a real-time clock (RTC).
- *Non-volatile memory.* To ensure forward progress despite frequent power outages, batteryless systems implement state retention mechanisms such as checkpointing, where the application state is copied to NVM before a power failure and can be restored once enough energy is available.
- *Flexible conversion circuits.* Each component has its own optimal operating voltage (minimizing the leakage or maximizing performance). As such, it is crucial to supply individual components with different voltages. This necessitates to translate the electrical signals between devices.

Whilst some batteryless systems do provide these components, they are restricted by design to specific applications (i.e., they have a single-purpose use [1, 2]) or are tied to a specific target device (with the `Riotee` board by Nessie Circuits [3] being an example of this). `Riotee` offers an all-in-one solution with various shields to simplify custom application development. However, when it comes to adaptability, existing setups cannot easily be converted to batteryless operation without significant hardware modifications due to fixed CPU, memory size, and voltage thresholds. Hence, we aim to design a board providing greater modularity and flexibility, while allowing seamless integration into existing systems (i.e., a more versatile solution for a wider range of IoT applications).

Contributions. We fill this gap by introducing BPMx, an extension board to build batteryless systems offering an unprecedented level of flexibility in the choice of target device and harvester, as well as providing all aforementioned features (fully adaptable to the specifications of the target device with a user-specified operating voltage from 1.8 V to 3.3 V). Possible target devices include the popular `nRF52840-DK` and `STM32L152` Nucleo among a myriad of other compatible boards sharing the official `Arduino Rev3` pin layout.



(a) High-level architecture **(b) PCB prototype** **(c) Charging/discharging cycle**

Figure 1: Overview of BPMx's design: (a) high-level architecture (highlighted in brown), (b) realization as a prototype PCB designed to fit onto an Arduino, and (c) operating stages illustrated via a typical charging/discharging cycle.

2 BPMx: Overview

We detail next the design of BPMx: as shown in Fig. 1a, BPMx allows to connect an arbitrary energy harvester to a target device in order to enable its batteryless operation.

Architecture. Fig. 1a also provides a high-level overview of BPMx and its key modules. BPMx receives power from an externally connected energy harvester, which allows to load a supercapacitor[1]. It then uses a *power management* circuit to dynamically power the target device. Once the set threshold is reached, a comparator enables the main power converter (a configurable TPS62743 buck-converter) powering the target device. When powered, the target device communicates with BPMx primarily via I^2C, but a few interrupt lines can also be used for time-critical responses. Fig. 1b shows the current BPMx's prototype[2], with 25 jumpers allowing to easily configure thresholds, voltage, and to disable various segments of the circuit. The jumpers also allow to select the target's supply voltage in the range [1.8-3.3] V.

Efficient timekeeping. BPMx embeds an Artasie `AM1805` real-time clock with power management, which maintains the active power state and keeps track of the time during the off-state of the target device. Its built-in power switch controller allows the target to turn itself off via software for a certain amount of time (ultra-low-power sleep). Depending on the target's operating voltage, it is most efficient to power the RTC as high as possible to take the most advantage out of its standalone backup capacitor, which holds on up to 20 more minutes of timekeeping during a total power loss. Therefore, we provide a selectable LDO regulator as a second power converter, providing 3.5V to guarantee the best behavior. An additional I^2C-level shifter can also be selected to compensate for this possible voltage difference.

Voltage monitoring. To monitor the supercapacitors' voltage, BPMx incorporates the `TI ADS7142`. This analog-to-digital converter (ADC) embeds the ability to promptly detect power failures, even during ultra-low-power sleep – a feature that is fully configurable in software. To ensure consistent ADC measurements (the ADC runs at the selected main voltage), BPMx also includes a fixed voltage divider.

Persistent memory. Our current BPMx prototype embeds a Fujitsu `MB85RC512T` with 512kb of FRAM (*NVM*), which allows to persistently save data. Furthermore, the FRAM is directly power-gated by the target node to save energy.

Low power consumption. Our BPMx prototype features an ultra-low-power sleep current as low as 13.6 µA and a quiescent current as low as ≈ 30 µA for the running state. These current levels depend on the configuration of BPMx and can vary across different setups (e.g., not power-gating the FRAM results in ≈ 15 µA extra current).

3 Showcasing BPMx

In our demo, we attach BPMx to an `nRF52840-DK` alongside an external sensor, implementing a periodic sensing application powered by an intermittent source of energy. The RTC is used to schedule a periodic sensing task (*active*), during which the device either saves the measurements onto the FRAM or, depending on the charge left in the capacitor, *transmits* them wirelessly using IEEE 802.15.4 and otherwise *sleeps* to save power. We will show that BPMx can accurately respond to voltage drops, trigger the creation of checkpoints from the target device, and power gate its various components via software to save additional power. To highlight BPMx's ease of configuration, we will bring along different instances of BPMx, so to demonstrate a range of possible configurations to the audience.

Our demo will also show how BPMx allows to inspect/control the charging/discharging cycle of an intermittently-powered device. An example of such charging cycle is depicted in Fig. 1c. Reaching the on-threshold of the comparator ① enables the main power converter and, therefore, the target node. The target then checks the FRAM for valid checkpoints and starts its workload. During ②, the capacitor discharges until the voltage reaches a defined lower limit ③, where the ADC informs the target to create a checkpoint before the power cuts off. While the target is off ④, the RTC keeps tracking time until the voltage is sufficient again.

References

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[1] In the current prototype, the user can solder two supercapacitors: one SMD, and one through-hole, enabling them individually via a dedicated jumper.
[2] The BPMx schematics are available *open-source*: http://iti.tugraz.at/BPMx.