Energy-aligned Wake-up Scattering for Batteryless Devices

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Abstract

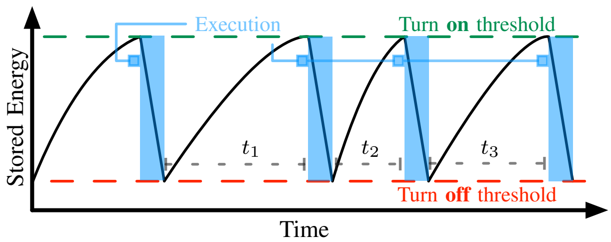
Batteryless systems promise a revolution in the Internet of Things (IoT) by eliminating the need for batteries, thereby reducing maintenance costs and environmental impact. However, these systems face significant challenges in energy management, which become even more complex when devices are required to collaborate with one another. In this demo, we showcase *ScAlg*, a decentralized algorithm that leverages wake-up receivers to scatter wake-up times within a fully connected network of batteryless devices. This approach improves operational continuity and reliability under strict energy constraints. Our hardware setup demonstrates how batteryless nodes utilize wake-up receivers to coordinate their wake-up schedules based on energy availability dynamically, enabling sustained operation and collision-free communication.

I. Introduction

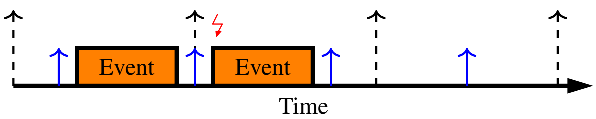
The Internet of Things (IoT) connects numerous devices to improve daily life, but reliance on batteries creates challenges like maintenance, environmental impact, and limited lifetime. Batteryless systems that harvest ambient energy (solar, thermal, kinetic) offer a promising alternative by eliminating batteries.

However, these systems face strict energy constraints, complicating continuous operation (Figure 1a). Using multiple batteryless devices collaboratively might improve the quality of service, but coordination is difficult; uncoordinated wake-ups may cause redundant data or communication collisions (Figure 1b).

Existing approaches avoid energy-intensive communication and rely on statistical methods. For example, [2] leverages hardware variations to scatter wake-up times for devices with equal energy, while Islam et al. [3] propose Prime-Co-Prime duty cycles and Dec-POMDP-based adaptive scheduling for nodes with differing or dynamic energy availability. Although communication-free, these methods heavily depend on assumptions about factors



(a) Basic operation of a single intermittent system [1]. Depending on the energy availability, the system can either be in an active state (blue) or in a sleep/off state (white). The system is only able to perform tasks when it has enough energy available.



(b) Possible scenario with two batteryless devices (blue and black dashed). The arrows indicate the devices' wake-up times. The figure illustrates a case where the nodes have differing energy availability. Without considering the relative alignment of wake-up times, the devices may wake up simultaneously, resulting in redundant data collection or potential data loss due to collisions. In event detection scenarios, this misalignment can lead to missed events.

Fig. 1: Timely behavior of batteryless devices.

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such as energy availability patterns and device properties, which limit their ability to accurately predict wake-up times in dynamic or heterogeneous scenarios.

To address these challenges, we showcase *ScAlg* [4], a decentralized algorithm that leverages wake-up receivers to intelligently scatter the wake-up times of batteryless devices, enhancing their coordination and reducing collisions in energy-constrained networks.

II. ScAlg

ScAlg is a distributed algorithm enabling energy-aware cyclic task execution in fully connected networks of batteryless sensor nodes performing identical tasks periodically.

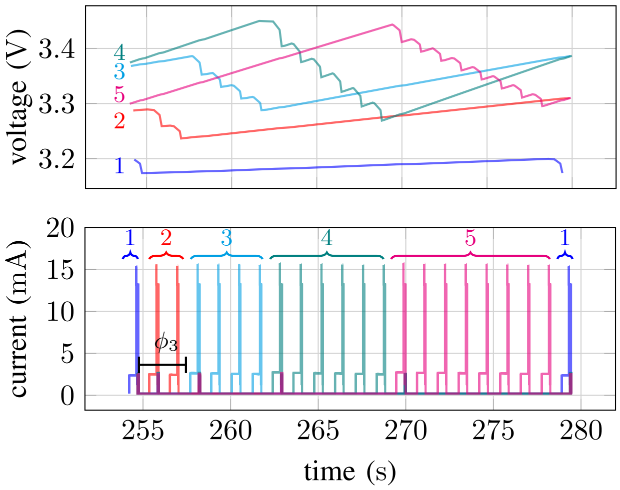


Fig. 2: Simulated capacitor voltages and current consumptions for five nodes running *ScAlg*. Charging power ranges from $1\,\mathrm{mW}$ - $3\,\mathrm{mW}$. Intersamplingrates are calculated based on the slowest node's cycle period, allowing nodes with higher energy availability to execute tasks more frequently within the slowest node's cycle.

Each node autonomously determines its sampling period based on its current harvesting power P_{harv}, task power consumption P_{task} and execution time t_{task}, and the node's power consumption in sleep mode P_{sleep}. The cycle period T is determined as

$$T = \frac{P_{\text{task}} - P_{\text{sleep}}}{P_{\text{harv}} - P_{\text{sleep}}} \cdot t_{\text{task}},$$

where $P_{\text{harv}} > P_{\text{sleep}}$ is required. Nodes usually have different energy availability, resulting in different cycle periods T_i. Instead of enforcing a uniform slowest period T_{s}, *ScAlg* leverages an intersampling rate

$$R_i = \frac{T_{\text{s}}}{T_i},$$

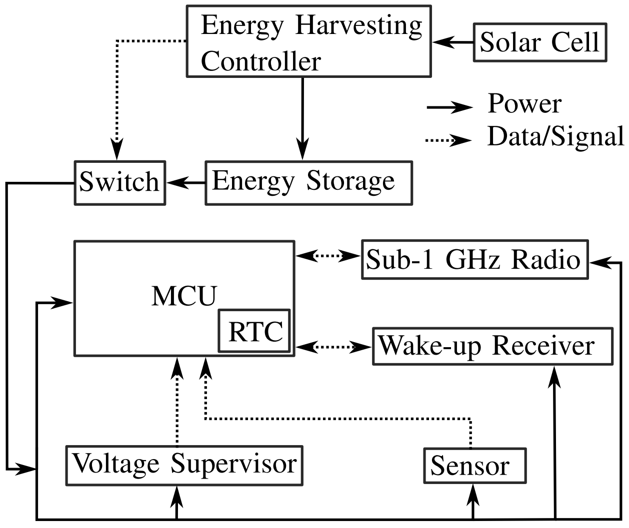
allowing nodes with higher energy intake to execute tasks more frequently (*intersampling*) within the slowest node's cycle T_{s}.

Nodes exchange their sampling periods via wake-up receiver messages, allowing calculation of intersampling rates and synchronized, staggered task execution. The distributed sampling interval becomes

$$T_{\text{d}} = \frac{T_{\text{s}}}{\sum_{i=1}^{N} R_i},$$

and each node schedules its task with a relative shift to the slowest node, defined as

$$\phi_i = \left(\sum_{k=1}^{i-1} R_k\right) \cdot T_{\text{d}} - t_{\text{task}}.$$



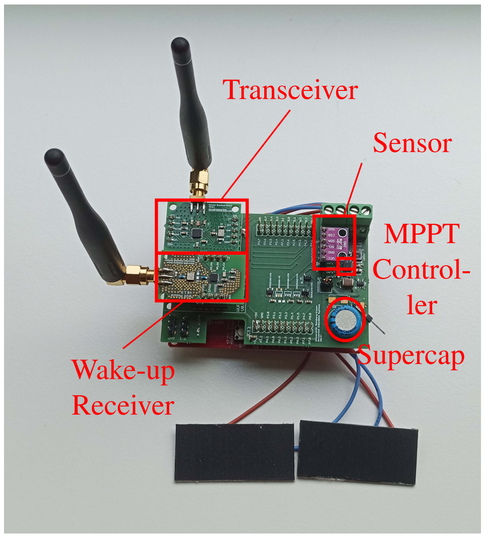


Fig. 3: Hardware used to evaluate *ScAlg*. The left image illustrates the architecture of the sensor node [5], while the right image displays the sensor node with its key components annotated.

The slowest node triggers its cycle based on its energy storage voltage, acting as the network's heartbeat. Other nodes synchronize their schedules upon receiving its wake-up messages, enabling dynamic adaptation to energy variations and seamless integration of new nodes.

This approach ensures efficient, energy-aware cyclic sensing in networks of batteryless nodes without sacrificing performance of devices with higher energy availability. An example distribution of the wake-up times is shown in Figure 2, where nodes with different energy levels adapt their sampling periods and intersampling rates to achieve a network wide equidistant and periodic task execution.

III. Hardware and Demonstration Setup

We utilize the hardware described in [5] (see also Figure 3), which consists of a batteryless sensor node powered by a solar cell as its energy harvesting source. The solar cell is connected to a maximum power point tracking (MPPT) controller and can harvest up to approximately $500\,\mathrm{mW}$. The energy is stored in a capacitor with a capacitance of $47\,\mathrm{mF}$.

The node also incorporates a wake-up receiver (WuR) alongside a transceiver. The WuR supports three addressing modes—unicast, multicast, and broadcast—enabling selective wake-up of nodes. Additionally, it can receive up to five bytes of extra data, facilitating broadcasts. Nodes can synchronize on incoming messages, as the WuR signals a wake-up ID match by asserting a GPIO pin that triggers an interrupt on the microcontroller.

According to the datasheet [6], the WuR consumes $< 3.5\,\mu\mathrm{A}$, making data reception more energy-efficient compared to traditional transceivers. For reference, the CC1101 transceiver draws roughly $15\,\mathrm{mA}$ when in RX mode [7].

We invite attendees to witness a live comparison of two sets of batteryless IoT devices operating under the same environmental conditions. The first set uses *ScAlg* to coordinate wake-up times and distributed task execution adaptively. The second set operates without any scattering algorithm, resulting in uncoordinated wake-ups that cause communication collisions and redundant data.

The demo setup will:

1) Show two sets of batteryless devices, one using *ScAlg* and the other using no wake-up scattering algorithm.
2) Visualize devices' wake-up schedules in real-time via LEDs, with the first set showing coordinated wake-ups and the second set showing uncoordinated wake-ups.
3) Demonstrate how *ScAlg* adapts wake-up schedules based on energy availability.
4) Demonstrate ease of deployment and scalability in fully connected batteryless networks with wake-up receiver support.

Attendees will see firsthand how coordination via *ScAlg* enhances network reliability and energy utilization, a significant step forward for sustainable IoT deployments.

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