Demo Abstract: Detailed Recording and Emulation of Spatio-temporal Energy Environments with SHEPHERD*

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ABSTRACT

Collaboration of batteryless nodes is essential to their success in replacing traditional battery-based systems. This abstract describes a demonstration of the recently proposed SHEPHERD testbed that allows to record and reproduce spatio-temporal characteristics of real energy environments. It consists of a number of spatially distributed SHEPHERD nodes that are tightly time-synchronized with each other and record synchronized energy traces with a resolution of 3 µA and 50 µV at a rate of 100 kHz. Additionally, SHEPHERD can faithfully replay these traces to any number of nodes to study their behavior, both individually and as an ensemble. SHEPHERD works with various sources of energy harvesting, such as kinetic or solar, is based on a modular design and provides a generic interface for sensor nodes allowing users to experiment with new platforms.

CCS CONCEPTS

• **Computer systems organisation → Sensor networks**; **Sensors and actuators**; **Embedded software**;

KEYWORDS

Batteryless sensing, intermittent power, transient computing, energy harvesting, intermittent networking

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1 INTRODUCTION

As the Internet of Things (IoT) is expected to grow to trillions of devices [3], sustainability and reliability of this computing infrastructure become matters of utmost importance. One possible path to sustainability is the adoption of *batteryless* devices that buffer harvested energy in a capacitor, and execute when there is energy available in the capacitor. Batteryless devices promise to overcome the drawbacks of (rechargeable) batteries, such as bulkiness, wear-out, toxicity, uncertain remaining charge, etc. The limited energy capacity of capacitors, however, requires intermittently executing the software. Prior research and tools focus on enabling sensing and computation on individual intermittently powered sensor nodes [2].

To unleash their full potential and to eventually replace battery-supported devices, batteryless nodes must communicate and cooperate autonomously, without a continuously powered base station. Operating devices without energy storage in real energy environments results in varying intermittency patterns, as shown in Fig. 3, making communication extremely difficult or even impossible.

Understanding spatio-temporal characteristics of energy environments is essential to answer the questions if and how groups of batteryless devices can communicate. Once the conditions and requirements are understood, researchers can investigate techniques to enable communication and cooperation under these conditions. Experimental evaluation and comparison of these techniques by repeatedly emulating the same, realistic energy traces allows to identify viable strategies and to establish trust before deployment.

2 SHEPHERD TESTBED

In our SenSys 2019 paper [1] we introduce SHEPHERD, an affordable, open-source, and easy-to-use tool for the synchronized recording and emulation of spatio-temporal energy traces, enabling experiment-driven research into the most challenging problems towards a connected, batteryless future. The design and implementation of SHEPHERD is driven by four main design goals, as detailed below.

Portability. Energy environments are often unique in time and space. Users must thus be able afford to build and deploy SHEPHERD in different locations, which poses strict limitations on required infrastructure, costs, and physical dimensions.

SHEPHERD is built around compact and affordable SHEPHERD nodes that are based on the BeagleBone single-board computer and custom hardware. A SHEPHERD node is capable of recording or replaying harvesting traces independently with respect to its own clock. By synchronizing all SHEPHERD nodes using Precision Time Protocol (PTP) (indoors, wired) or Global Positioning System (GPS) (outdoors, wireless), energy and experimental traces can be related and replayed with respect to one common timeline.

Modularity. Users must be able to experiment with different energy-harvesting hardware and to emulate recorded traces against different sensor node platforms. To this end, the SHEPHERD hardware is divided into the following key parts: The *SHEPHERD cape* is stacked on top of the BeagleBone and hosts the recording and emulation circuits. Different harvesters can be connected through the *harvesting capelet*. The *storage capelet* is a small board that allows to easily

*https://shepherd.nes-lab.org

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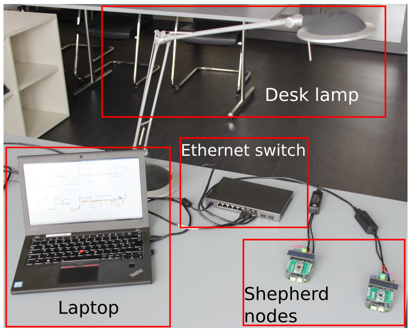

Figure 1: The demo setup consists of a number of SHEPHERD nodes connected and time-synchronized over an Ethernet switch. The demo is controlled from a laptop, allowing users to see the commands used and interactively view the results of the experiment.

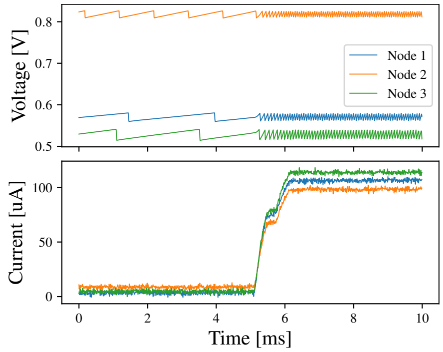

Figure 2: Harvesting voltage and current on three SHEPHERD nodes equipped with solar panels. After around 5 ms, a light source is switched on. The voltage regulator increases its switching frequency and the current sharply rises synchronously on all three nodes.

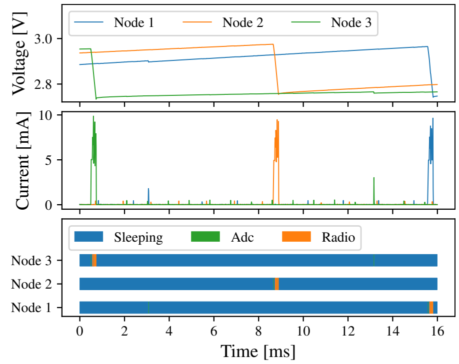

Figure 3: Capacitor voltage and supply current into three batteryless sensor nodes. When the capacitor voltage reaches a turn-on threshold, the nodes power on and send three BLE packets, quickly draining the capacitor.

exchange the storage capacitor. The *target capelet* connects to SHEPHERD through a well-defined header, exposing the capacity-buffered supply voltage and level-translated UART, GPIO, and debug signals.

Performance. Harvesting conditions may change rapidly, requiring signals to be sampled with a frequency of 100 kHz. Additionally, current may vary over a wide dynamic range from 1 µA to tens of mA. In order to meaningfully relate traces from different nodes, the synchronization error must be smaller than 1 µs.

Usability. To make SHEPHERD a successful testbed, users must be able to install and use the complex stack of hardware and software components with ease. This is achieved by (*i*) using well established IT automation tools for installation, (*ii*) a modular software stack with well-defined interfaces, and (*iii*) extensive documentation.

SHEPHERD is the first energy-harvesting testbed that meets these requirements through a careful co-design of hardware and software.

3 DEMO SETUP

Fig. 1 shows the demo setup. It consists of three SHEPHERD nodes equipped with solar panels that are connected and synchronized over Ethernet. We use a desk lamp to create a dynamic energy environment. Each SHEPHERD node is connected to a sensor node for emulation. We showcase the full experiment cycle, from recording to emulation using the corresponding analysis steps, so interested attendees can experience the end-to-end usage of SHEPHERD.

Recording. We record solar energy-harvesting trace for one minute while attendees can cover individual solar panels or switch the lamp on/off. The sensor nodes use the available energy during recording to run a simple intermittent application: Each node waits until its storage capacitor charges above a turn-on threshold and switches on an LED until the voltage drops below a turn-off threshold. This results in a distinctive blinking pattern across the three devices, depending on the harvesting conditions created by the attendees.

Harvesting analysis. Afterward we plot the recorded data, allowing attendees to identify their actions during recording in the voltage and current traces. For example, attendees can see how the current sharply rises in response to the light source being switched on (see Fig. 2) or the drop when individual panels are covered.

Emulation. Next, the recorded traces are synchronously played back to the sensor nodes running the same application as during recording. During emulation, SHEPHERD records the capacitor voltage and supply current into the nodes as well as GPIO traces encoding the internal application state on each node. Attendees are able to observe the same blinking pattern on the nodes as during recording. This effectively demonstrates the repeatability of experiments with SHEPHERD using a deterministic application logic.

Emulation analysis. Finally, we plot capacitor voltage, supply current, and application state collected during emulation. This demonstrates the ability to analyze the behavior of groups of batteryless sensor nodes while they are exposed to given energy conditions. In these traces, attendees are able to identify one of the central challenges towards autonomous communication between intermittently powered devices: Without appropriate strategies, the chance that two devices have enough energy at the same time and thus would be able to exchange messages is small. This is shown in Fig. 3.

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