Demo Abstract: Bootstrapping Batteryless Networks Using Fluorescent Light Properties

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ABSTRACT

Communication among batteryless devices is key to their success in replacing traditional battery-supported systems. However, low and unpredictable availability of ambient energy combined with limited energy storage capacity of the devices make *efficient* communication challenging. As a stepping stone toward addressing this challenge, we propose to leverage common patterns in harvested energy across the devices. In this abstract, we explore one possible approach that exploits a property of many fluorescent light sources used worldwide: their brightness changes with double the power line frequency. We design a circuit that transforms the corresponding changes in energy harvested with a solar panel into a digital signal that is frequency- and phase-synchronized across multiple devices. Based on our design, we build a novel batteryless node, called Flync. Using two Flync nodes, we demonstrate that the synchronized signal can be generated with less than 1 µA and a maximum measured node to node jitter of 363.24 µs.

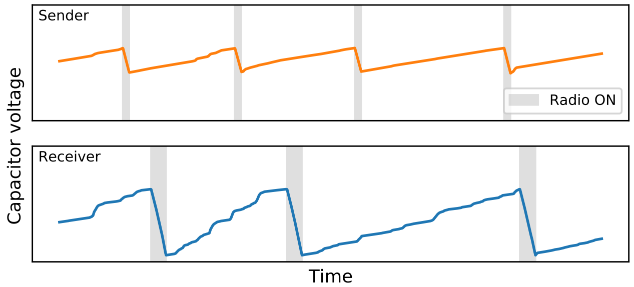
KEYWORDS

Batteryless networks, Energy harvesting, Fluorescent light, Rendezvous, Timekeeping, Synchronization, Wireless communication

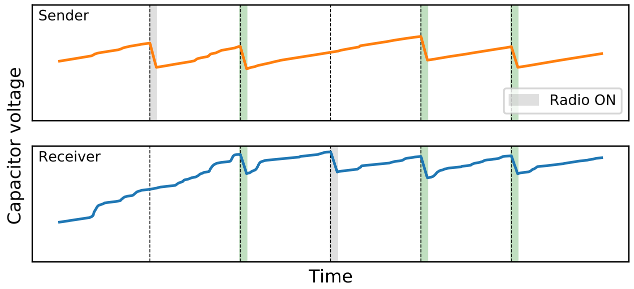
1 INTRODUCTION

As the Internet of Things (IoT) grows to trillions of tiny embedded devices [3], its sustainability becomes a matter of utmost importance. Batteryless devices promise to overcome the drawbacks of (rechargeable) batteries; however, to unleash their full potential and to replace battery-supported systems, they must be able to communicate and cooperate efficiently despite frequent, non-deterministic power failures and varying energy budgets at individual nodes. To address these challenges, two key problems must be solved.

Initial rendezvous. Batteryless nodes lose track of time during extended periods without energy. After every such power failure, nodes need to re-synchronize during an initial encounter (or *rendezvous*), where both communication partners are active. This is difficult given the limited, asynchronous duty cycle resulting from low energy availability and small energy storage, as shown in Fig. 1a.



(a) Initial rendezvous without a common time reference.



(b) Initial rendezvous with a common time reference (dashed lines).

Figure 1: Because of low and unpredictable duty cycles the time until the initial rendezvous after a power failure can be prohibitively long. Using a common time reference, the chances for successful rendezvous increase dramatically.

Timekeeping. After the initial rendezvous, nodes may agree on a wake-up schedule that is sustainable for both of them. To operate according to the common wake-up schedule over long connection intervals, nodes require a highly stable clock. Such a clock typically draws orders of magnitude more power than what is available to a batteryless node. For example, the high-frequency clock of our Flync prototype based on the nRF52840 (see Fig. 3) consumes at least 750 µW, while we harvest at most 50 µW from ambient light.

Both problems can be solved using a common frequency- and phase-synchronized signal that is used as a time reference by all nodes. This time reference induces a global time grid, which can greatly reduces the cost of the initial rendezvous: If energy allows, nodes can turn on their radios *simultaneously* for a short time, as shown in Fig. 1b. Furthermore, as different nodes measure time with respect to the *same* signal, there is no drift among the nodes. This removes the need for a stable, yet power-hungry local clock.

To obtain a common frequency- and phase-synchronized signal, we propose to exploit common patterns in harvested energy. The basic idea is that nodes that wish to communicate are often close by

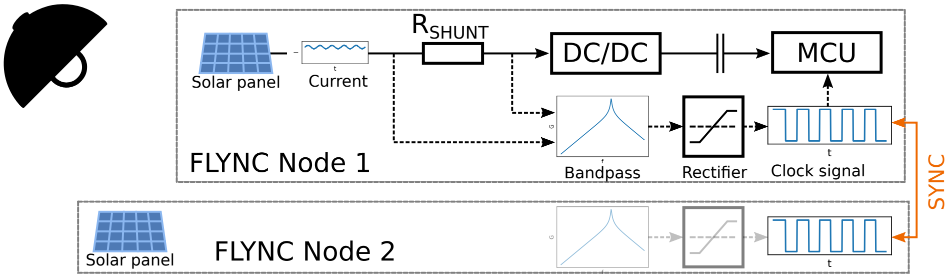


Figure 2: Overview of demo setup and proposed approach to exploit the brightness variations in fluorescent light. The circuit we design consists of a shunt resistor, a band-pass filter to extract the power line frequency, and a rectifier to convert the sinusoidal solar current signal into a rectangular signal that can be used as a frequency- and phase-synchronized time reference for multiple batteryless nodes.

Figure 3: The Flync prototype based on the nRF52840. The solar panels on the backside charge a small capacitor that powers the circuit and the MCU.

and receive energy from the same source(s). Thus, they have access to a common (energy) signal that can be used as a time reference.

2 LEVERAGING INDOOR LIGHT VARIATIONS

One example cause of common patterns in harvested energy are brightness variations of fluorescent lamps, which are ubiquitous in buildings around the world. Their brightness periodically changes with double the power line frequency. Since lamps within the same room, floor, or even building are usually connected to the same power phase, the brightness of different lamps varies with the same frequency and phase, and thus the electromagnetic waves interfere constructively at the solar panels of different nodes. As a result, the power harvested by these nodes varies in the same way.

We design a circuit, shown in Fig. 2, that converts these power variations into a rectangular signal. When connected to the General Purpose Input Output (GPIO) pins of multiple microcontroller units (MCUs), this signal provides a frequency- and phase-synchronized time reference. The current draw of the circuit is less than 1 µA.

We build an ultra-low power batteryless node, called Flync, that integrates the proposed circuit and the popular nRF52840. Using our prototype, shown in Fig. 3, we record 1000 consecutive clock edges on two different Flync nodes with a logic analyzer. The measured time difference between any pair of corresponding edges has a mean of 19.39 µs and a maximum of 363.24 µs.

3 DEMO SETUP

The demo setup consists of two Flync nodes that are harvesting energy from fluorescent light and extract a synchronous rectangular time reference signal from the brightness variations induced by the power line. The signals of the two nodes are analyzed using a mixed-signal oscilloscope, allowing attendees to view the sinusoidal solar current and the time reference signal in real time.

4 RELATED AND FUTURE WORK

The synchronization of batteryless nodes has not been explored in the literature. We thus focus our review on approaches that utilize power line signals to provide accurate, frequency-synchronized reference clocks to battery-supported sensor nodes. These approaches rely on a wired connection to the power line [4] or use power-hungry hardware to synchronize to the electromagnetic radiation (*e.g.*, estimated 200 µW in [2]). Power line induced brightness variations of fluorescent light have also been used to calibrate the clocks of individual nodes by rapidly sampling a light sensor [1]. By contrast, we propose to use not only the frequency, but also the phase information of the common signal for efficient rendezvous and timekeeping. Further, our approach does not require additional sensors and consumes negligible additional power, making it suitable for ultra-low power batteryless nodes.

In future work, we intend to design a batteryless stack on top of Flync and explore the utility of Flync beyond batteryless systems.

ACKNOWLEDGMENTS

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