Cinamin: A Perpetual and Nearly Invisible BLE Beacon

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Abstract

Bluetooth Low Energy beacons have immense potential to provide rich contextual information to smartphone applications and people by bridging the physical and digital worlds. Beacons perform the simple operation of periodically chirping URLs, locations, and other pointers, however, today's beacons use relatively large and battery powered implementations. To truly make these beacons pervasive, they will need to be smaller, self-powered, and, ideally, invisible. To facilitate this, we propose the Cinamin beacon design that exploits the powerful but simple primitive of periodic packet broadcast to replace the volume-defining battery with an energy-harvesting power supply and achieve a beacon in under 100 mm^3. This design, however, raises new issues relevant to energy-harvesting and challenges with pursuing miniaturization.

1 Introduction

Bluetooth Low Energy (BLE) beacons enable a host of applications that blend physical and digital spaces. By embedding wireless communication that interoperates with smartphones, smart watches, and other wearable technology, beacons such as iBeacon [2] and Eddystone [1] allow people to connect seamlessly with their surroundings. Existing beacon hardware designs support these applications but are limited in two ways: 1) they rely on batteries, which have a fixed lifetime and will need to be replaced after a year or two, and 2) are noticeably large on account of including the volume of a battery. Common beacons run on a CR2032 battery and therefore are at least 1 cm^3 in volume. MEMS-scale beacons are not yet commercially available. Given the immense application space that leverages beacon-provided context information, can we build a better beacon that is small enough to be placed anywhere unnoticed, does not have a lifetime limitation, and can be built today with COTS parts?

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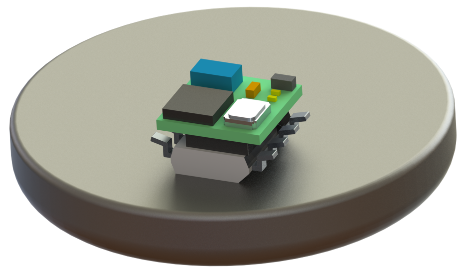

Figure 1: Cinamin BLE beacon model on a CR2032 coin cell battery. The radio, crystal, antenna, energy buffer, antenna, PCB, power supply, and solar panel all fit in a 5 mm x 5 mm x 3.4 mm cube.

To accomplish this, we propose replacing the battery-based power supply with an energy-harvesting design based on indoor solar. BLE beacons are well suited for energy-harvesting as they provide utility while requiring little device complexity: the device must only transmit the same packet periodically. Harvesting can potentially remove the lifetime constraint as the beacon can harvest whenever the lights are on (which is typically correlated with when people are around), and can drive down the form factor as a sufficient solar cell and buffer capacitor are smaller than a typical coin cell. One potential design is shown sitting on a CR2032 battery in Figure 1 and occupies 85 mm^3.

To understand the feasibility of this design point, we explore what energy budget a 5 mm x 5 mm solar panel may provide in an indoor setting, what the state-of-the-art BLE radios require in terms of startup, advertising, and sleep energy, and what low-power ICs exist for controlling the power supply in this energy-harvesting context. We analyze the two modes of operation for this energy-harvesting beacon: cold-booting before each transmission or maintaining low-power sleep, and note that startup energy costs often outweigh keeping the radio in sleep mode. We find that the components needed for this application are mostly available today, with size being the largest hurdle. Both indoor photovoltaics and energy-harvesting ICs need better options for miniaturization efforts.

Scaling BLE beacons down to fit unnoticed inside of light fixtures will significantly lower the bar for making immersive experiences possible, pervasive, and seamless.

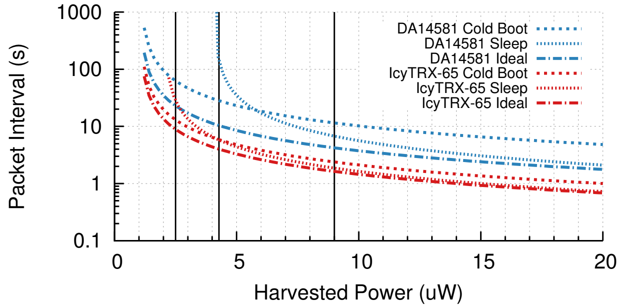

Figure 2: Beacon performance at different harvesting levels.

2 Design Tradeoffs

Three major components define the operation of the energy-harvesting BLE beacon: the harvesting source, the BLE radio, and the power supply.

2.1 Indoor Solar Harvesting

To estimate the amount of energy that can be harvested from indoor solar, we examine existing studies of indoor irradiance and indoor photovoltaic efficiencies. Yerva et. al [5] found that sensors placed indoors can expect an irradiance of about 100 uW/cm^2, and assuming an efficiency of 10% [4], a 5 mm square solar panel could harvest 2.5 µW. To improve this, the beacon may be placed closer to the light, and De Rossi et. al [4] found that for an amorphous silicon cell in 500 lux of florescent light could harvest 17.1 uW/cm^2. If placed very close to the light, or inside of the fixture, the beacon would likely be able to harvest more.

2.2 Beacon Operation

Because of its simple execution mode (send a BLE advertisement), the beacon can either stay off and cold boot before each transmission or transition to sleep mode when not active. The relation between incoming harvested energy and beacon period can be described as:

$$(P_{HARVEST} - P_{LEAK} - P_{SLEEP}) \cdot t_{period} = E_{STARTUP} + E_{ADV} \quad (1)$$

when the incoming power minus losses and the power to keep the radio in sleep over the period between transmissions must equal the energy needed to start the radio and transmit a packet. In cold boot mode, P_{SLEEP} will be zero, and in sleep mode $E_{STARTUP}$ will be zero. P_{LEAK} is the power lost due to leakage and the power supply overhead. Figure 2 shows the beacon interval time versus harvested power for two BLE radios, the Dialog DA14581 and the CSEM IcyTRX-65, that represent the lowest power radios available. Startup and advertising energy and sleep power numbers were obtained from [3] and relevant data sheets. For each radio there are curves for the two modes, plus an "ideal" case where both startup and sleep costs are zero. Marked with vertical lines are harvesting estimations from Section 2.1 and one at 9 µW that would likely be possible very near a light with a well matched solar panel at the 5 mm x 5 mm form factor.

At low harvesting levels (below 5.5 µW) it is better to cold boot the DA14581 before each transmission than try to keep the radio in sleep mode (which would likely be infeasible).

IC	I_Q	Voltage Divider Required	Size (mm^2)	Internal Power Gate
AKM AP4400A	20 nA	No	14.7	No
Analog ADM8642	92 nA	Yes	1.5	No
Linear LTC1540	300 nA	Yes	9.0	No
TI BQ25504	330 nA	No	9.0	No

Table 1: Comparison of potential harvesting solutions.

The lower power IcyTRX-65 radio displays less of a gap, but has a crossover point at 4.3 µW. Therefore, when targeting the extreme low end of harvesting and miniaturization, paying the startup energy cost before each packet allows for a higher advertising rate than maintaining sleep mode.

3 Challenges

Three main challenges exist for building this node today.

3.1 Energy-Harvesting Power Supplies

The beacon requires a power supply to buffer energy in a storage capacitor and monitor voltage to indicate when there is sufficient energy available to successfully transmit. Table 1 highlights four ICs that can be used for this type of power supply. To facilitate cold booting, the supply must be able to enable VCC to the radio and disconnect the radio to allow for recharging. Also, any quiescent current of the harvester or voltage monitor (P_{LEAK}) reduces the input power.

While we found no ICs that perfectly matched our goals, and none that included a power gate for enabling cold booting, the AKM AP4400A provides the best set of features, albeit in a rather large package and without configurable voltage thresholds. To better support these types of energy-harvesting applications, better ICs are needed that continue to minimize quiescent current while including configurable high and low voltage detection and internal power switches.

3.2 Indoor Photovoltaics

Current COTS solar panels provide little flexibility for small, indoor systems. The estimates in this work are linearly scaled figures from measurements taken with larger panels (at least 12x larger) as smaller panels largely do not exist. The ones that do include significant packaging overhead. Today, beacon size is often dictated and guided by the available solar panel sizes. More panel sizes and mounting options are required to facilitate this frontier of beacons.

3.3 Transmission Range

A small node necessitates a small antenna with little RF keepout room. The beacon must be able to transmit at least short distance (1-3 m), but limited range may be advantageous to prevent congestion and user confusion. Prototyping the beacon is required to evaluate this fully.

4 References

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[5] L. Yerva, B. Campbell, A. Bansal, T. Schmid, and P. Dutta. Grafting energy-harvesting leaves onto the sensornet tree. IPSN '12, 2012.