Using Ambient Bluetooth Low-Energy Signals to Calibrate a Crystal-Free Micro Mote

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ABSTRACT

A crystal-free micro mote removes the crystal oscillator, reducing the overall footprint and power consumption, but suffers from large frequency drift that can violate wireless communication protocols' specifications. We present a calibration method for a crystal-free micro mote that uses ambient Bluetooth Low Energy (BLE) advertisements as a reference, demonstrated on SCμM. Prior work relied on IEEE 802.15.4 beacons, but our approach only uses ambient BLE. A frequency sweep identifies valid advertisement channels and locks the local oscillator to a well-performing tuning setting. BLE packet intervals were characterized in busy and quiet environments, yielding sweep times as low as 6.86 s and 94.72 s, respectively.

CCS CONCEPTS

• **Hardware** → **Wireless devices**; • **Computer systems organization** → **Sensor networks**; • **Networks** → **Network measurement**.

KEYWORDS

Crystal-free, system on chip, ambient signals, calibration, single-chip micro mote (SCμM).

1 INTRODUCTION

The demand for millimeter-scale, low-power sensor nodes can be fulfilled with crystal-free SoC devices. In-silicon clocks require calibration due to a large initial startup offset and frequency drift caused by changes in temperature. This is critical because reliable wireless communications are dependent on accurate clocking that meets the protocols' specifications. Common devices like smartphones and IoT devices can be used as a frequency reference to calibrate the clocks needed to maintain wireless communications. Papers like [1–5, 7, 8] use IEEE 802.15.4 wireless communication signals to calibrate a crystal-free device. However, because the standard is less common, ambient IEEE 802.15.4 signals are less abundant.

This paper demonstrates a calibration method designed for a crystal-free System on Chip (SoC) device that utilizes ambient Bluetooth Low Energy (BLE) signals to identify a reference frequency to tune the local oscillator (used for radio communications). The platform used to demonstrate this was the Single-Chip micro-mote (SCμM) [6]. To evaluate the expected real-world calibration performance (in terms of sweep time), ambient BLE data was collected in different locations, which represent both a dense and sparse packet density environment.

Table 1: SCμM Calibration Papers Summary

Year	Paper	Calibration Method
2019	Experimental Clock Calibration [7]	IEEE 802.15.4 RF-based calibration.
2019	Dynamic Channel Calibration [8]	Startup frequency sweep across channels and continuous IEEE 802.15.4 RF-based calibration.
2020	6TiSCH on SCμM [1, 4]	Two-stage initial calibration, optical bootloader pulses + RF-based (IEEE 802.15.4) calibration, followed by a digital trimming compensation algorithm.
2021	QuickCal [2]	Assisted calibration using a QuickCal Box before joining the network (IEEE 802.15.4).
2022	Surviving the Hair Dryer [3]	Continuous RF-based (IEEE 802.15.4) calibration under rapid thermal variation.
2024	Inter-Cal [5]	RF-based (IEEE 802.15.4) calibration without a crystal reference-based node.

2 CALIBRATION METHODOLOGY & SETUP

This work's calibration methodology is derived from [3, 5, 7], adapting the basic frequency sweep algorithm from prior work to BLE. While in receive mode, the chip performs a LO frequency sweep (LC oscillator sweep) across the 2.4 GHz BLE band (Fig 1a). For this work, it is sufficient to target a signal advertisement channel. The LC tuning is controlled by a coarse, mid, and fine register (5-bit). A frequency span of roughly 25 MHz is equivalent to a single coarse sweep, settings 20.0.0 to 20.31.31 (coarse, mid, fine). Which is greater than the frequency gap between advertising channels 37 and 38. The chip has an initial calibration through its optical bootloader, and the starting LO frequency is just below the first BLE advertisement channel 37 (20.0.0). After the sweep has concluded, the LO is locked to a valid BLE channel frequency using the previously saved tuning settings. When packets are correctly received on multiple tuning settings, due to tuning frequency overlap or a second advertisement channel detected, the configuration with the most packets received is used. A more robust implementation can be further implemented based on past work [5], making fine adjustments to the other on-chip clocks.

The sweep time is calculated using Eq.(1). The total sweep time (TST) is equal to the number of LC tuning settings ($settings_{total}$) needed to sweep a single course multiplied by the minimum amount of time needed to listen at each setting to receive one or more packets (Lt_{min}). A total number of settings is equal to the maximum number of mid settings multiplied by the maximum number of fine settings, thus being 1024 (32×32). The 2X multiplier in Eq.(2)

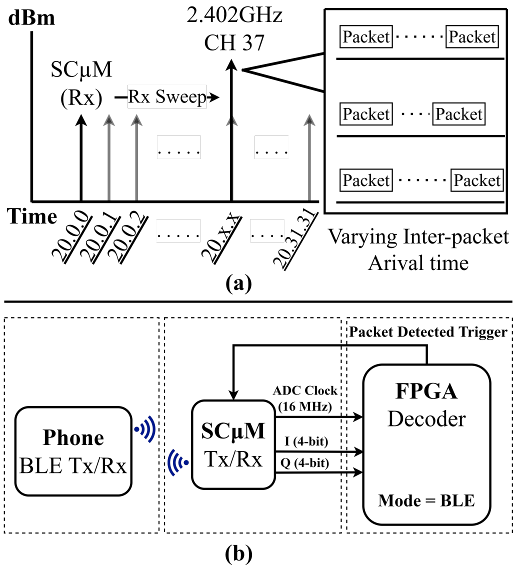

Figure 1: (*a*) Frequency sweep targeting a BLE advertisement channel (37). (*b*) A simple block diagram of the hardware configuration.

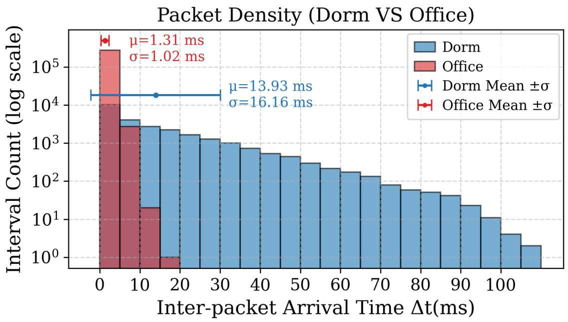

Figure 2: The packet intervals received by the BLE sniffer in each environment over a 6-minute period. Dorm RSSI = -80.02 dBm (σ = 8.18 dBm), office RSSI = -73.36 dBm (σ = 9.16 dBm). Total dorm packets = 25,846, total office packets = 275,406. Dorm PI_{max} = 107.50 ms, office PI_{max} = 19.06 ms.

and Eq.(3) is for redundancy to ensure that at least two packets are received. However, Eq.(3) can be used in place of Eq.(2) at the cost of robustness.

$$TST = setting_{total} \times Lt_{min} \tag{1}$$

$$Lt_{min} \leq 2 \times PI_{max} \tag{2}$$

$$Lt_{min} = 2 \times (PI_{\mu} + 2\sigma) \tag{3}$$

3 RESULTS

Fig 2 plots the histogram of the packet intervals (PI), start-to-start, at each location over a 6-minute interval. The calibration performance is evaluated using the total sweep time (TST). The calculated TST (Eq.(1)) in the dorm environment is expected to be 220.16 s when using PI_{max} (Eq.(2)) and 94.72 s using the mean and standard deviation (Eq.(3)). This is a reduction of 56.98% between the two implementations. For the office environment, the expected TST is 39.03 s using Eq.(2) for and 6.86 s when using Eq.(3). In the office environment, there is a reduction of 82.42% between the calculation methods. The TST percent difference between the two environments when using Eq.(3) is 172.99% (87.86 s).

4 CONCLUSION

This work shows that ambient BLE advertisements can effectively calibrate a crystal-free SoCs LO. A simple sweep algorithm is used to target BLE advertisement channels to find a precise reference. Ambient packets replace dedicated beacon nodes, and network sync (bidirectional communication) is not required. By collecting distribution data for the environment, we can leverage the mean and standard deviation to further decrease sweep times. The data collected can be used as a benchmark to evaluate the practicality of using ambient BLE for other spaces.

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