Industrial IoT with Crystal-Free Mote-on-Chip

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Abstract

SCμM is a 2×3×0.3 mm^3 system-on-chip that contains an ARM Cortex-M0 and a 2.4 GHz IEEE802.15.4 radio. This paper describes the two-step calibration routine needed to run a full 6TiSCH stack on SCμM. It is, to the best of our knowledge, the first time a fully standards-compliant protocol stack runs on a crystal-free radio, such that it can participate in a network with off-the-shelf radios.

Keywords: 6TiSCH, crystal-free, IoT, IEEE802.15.4, TSCH.

Introduction

The Single-Chip Micro Mote (SCμM, Fig. 1) is a 2×3×0.3 mm^3 system-on-chip that contains an ARM Cortex-M0 and a 2.4 GHz radio compatible with IEEE802.15.4 and BLE [1]. Unlike existing radios, SCμM only requires an antenna and a power source, no external crystal oscillator. SCμM realizes the "Smart Dust" vision by offering standards-compliance: it communicates with off-the-shelf radios.

Applications such as smart wearables or microrobotics require dependable networking between SCμM chips. A reference standardized Industrial Internet of Things protocol stack is 6TiSCH [2], standardized by the Internet Engineering Task Force (IETF). We were able to run the 6TiSCH stack on a SCμM using an external crystal oscillator [3]. The work we present here is the first to show the 6TiSCH stack running on SCμM with no crystal oscillator.

Calibrating SCμM's Oscillators

Without a crystal oscillator, SCμM relies on a free-running 2.4 GHz RF LC oscillator for tuning the communication frequency. Three separate RC oscillators are used to generate the transmitter chipping rate (2 MHz), clock the receiver (64 MHz), run the micro-controller (5 MHz), and drive the scheduling timer. These oscillators exhibit a clock drift of up to 16,000 ppm over an 80 min 25-70 C temperature ramp, compared to 10-40 ppm for typical crystal oscillators. Calibrating these oscillators is a significant challenge because of the non-linearity of the tuning, and the 40 ppm target. This paper uses two successive calibration steps.

We use optical calibration to provide an initial coarse calibration to all four oscillators. SCμM contains a photodiode and the circuitry for an optical programming board to load firmware onto SCμM using an LED [4]. We augment this by having the LED send a specific 32-bit sequence that triggers an interrupt on the micro-controller 100 times after loading the binary, with a 100 ms period. At each LED sequence, SCμM stores the value of the clock counters for calibration (Fig. 2). This is sufficient to initially calibrate the RC oscillators with enough accuracy to establish communications.

To calibrate the RF oscillator, we calibrate against a "QuickCal box": 16 off-the-shelf IEEE802.15.4-compliant devices (OpenMote) programmed to transmit a beacon frame every 600 μs, each on one of the 16 IEEE802.15.4 2.4 GHz frequencies. Calibrating the RF oscillator consists of adjusting three 5-bit capacitive tuning DACs. As shown in Fig. 3, SCμM first sweeps through 1024 radio RX settings, listens on each for 800 μs, and records the radio setting for each of the beacons received. Frequency calibration for RX and TX are independent. SCμM therefore sweeps a second time to calibrate radio TX settings by transmitting a frame every 1.32 ms and listening for an acknowledgement frame. RF calibration takes a total of 174 s, including the time for receiving the first frame from the QuickCal box. This version of SCμM has not been fully optimized for energy, the active power of the entire system is 1 mW.

Running Industrial IoT protocol

After calibrating against the QuickCal box, SCμM takes an average of 3.2 s to synchronize to an in-range OpenMote running TSCH. SCμM's timers are designed for running the 6TiSCH stack: during a 20 ms timeslot, SCμM's advanced timers orchestrate the execution of a timeslot state machine without microcontroller intervention (Fig. 4). This removes the need to wait for the microcontroller to be active, resulting in a potentially shorter timeslot and reducing energy consumption.

After optical and RF calibration, SCμM runs the full 6TiSCH protocol stack and communicates with an OpenMote, forming a 6TiSCH network (Fig. 5). After joining the network, SCμM relies only on receiving periodic beacon frames from the OpenMote for re-calibration. Fig. 6 indicates SCμM stays synchronized to the 6TiSCH network as long as an OpenMote in range sends a beacon at least once every 440 ms.

Future work involves the extension of the temperature compensation used in [1] to apply frequency corrections derived from network traffic to all the free-running oscillators.

References

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