Solar-Powered Crystal-Free 802.15.4 Wireless Temperature Sensor

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***Abstract*—We demonstrate a wireless temperature sensor consisting of only a chip with an ARM Cortex-M0 and radio, a mm-scale solar panel, and one surface mount capacitor. The radio lacks a crystal reference in favor of other on-chip oscillators to reduce cost and size. Without an absolute time reference, the on-chip oscillators need to be calibrated because their frequencies vary with supply voltage and temperature. An initial optical calibration procedure is used along with temperature-based compensation. This enables the radio to properly transmit standards-compatible IEEE 802.15.4 wireless packets over a temperature range from 35.5 C to 40.0 C. The standard deviation of the temperature estimate error relative to a reference is 0.28 C. The power for all of the components, including the radio and the microprocessor, is supplied by a solar panel on a CMOS chip under 200 mW/cm2 of irradiation.**

***Index Terms*—Wireless Temperature Sensor, Crystal-Free Radio, Local Oscillator Compensation, Autonomous Sensor**

I. Introduction

Autonomous micro-systems are challenging to develop because they integrate multiple subsystems, such as a power source and low power electronics for sensing, control, and communication. Nevertheless, there have been impressive results in autonomous wireless sensors and mesh networks [1].

The Michigan Micro Mote [2] is a $2{\times}4{\times}4\,mm^3$ wireless imaging system with an integrated processor, radio, battery, and solar cells. Fetik et al. [3] demonstrated a $8.75\,mm^3$ energy-autonomous temperature sensing system with a battery, solar cells, and an ARM Cortex-M3 operating at 7.7 µW. Wu et al. [4] use a Cortex-M0+ processor on a $0.04\,mm^3$ programmable temperature sensor system featuring 2-way optical communication and a base-station generated clock reference.

Previous autonomous micro-systems usually use custom ASICs, optical communication [4], or external clock references. The Single-Chip Micro Mote (SCµM), however, integrates a full microprocessor and crystal-free standards-compatible 802.15.4 radio. SCµM has operated before as an H_2S gas sensor [5], a cm-accuracy 3-D localization sensor [6], and as a controller to actuate MEMS grippers [7], among other applications. This work integrates SCµM [8], a solar panel (Zappy2) [9], and an 100 µF 0805 capacitor into an autonomous solar-powered wireless temperature sensor. This integration is challenging due to energy constraints, large voltage variations, and clock calibration requirements.

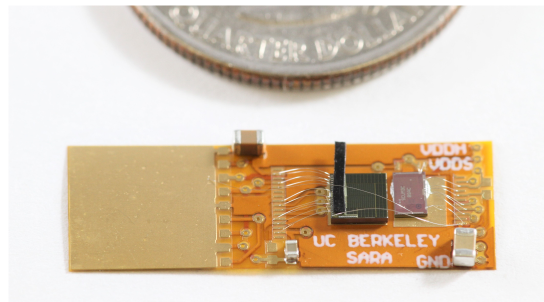

Fig. 1: Pad for future MEMS integration, HV buffer & solar cells chip, and SCµM (left to right). Only the capacitor on the bottom right is used while the remaining capacitors will be used for future MEMS integration.

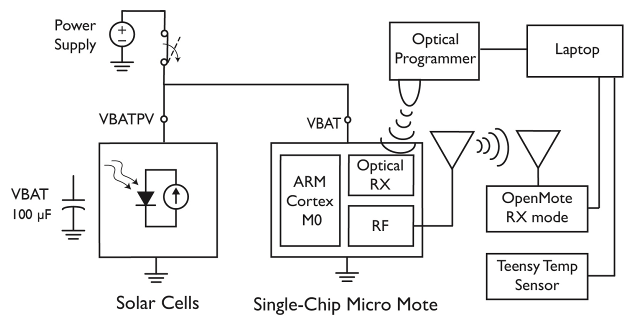

Fig. 2: System Diagram

II. System Description

A. Single-Chip Micro Mote (SCµM)

SCµM is a $3{\times}2{\times}0.3\,mm^3$ system-on-chip designed to be a low-cost, low-power wireless sensor node. It features an ARM Cortex-M0 microprocessor, a standards-compatible 802.15.4 radio, and an optical receiver and requires just a 1.5 V power supply to operate [8]. Notably, it does not require a crystal as a frequency reference. SCµM instead features several tunable CMOS oscillators [10], including a 20 MHz RC oscillator used to generate the clock for the Cortex microprocessor, a 2 MHz RC oscillator used as the chipping clock for 802.15.4 transmission, a 32 kHz oscillator used as a low-power sleep timer and a 500 kHz RF timer used to generate interrupts based on user-defined counters or the RF controller. SCµM uses a 2.4 GHz LC oscillator as its local oscillator (LO) to dictate the

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802.15.4 channel frequency. The LO frequency can be tuned by a 15-bit capacitive DAC, split into three 5-bit capacitive DACs called the coarse, mid, and fine codes [11].

Operating without a crystal reference means that SCμM's size and production costs can be further reduced. However, SCμM's oscillators are sensitive to the supply voltage and temperature. For example, the temperature coefficients of the 2 MHz and the 2.4 GHz oscillators are 160 ppm/°C [12] and −40 ppm/°C [8], respectively.

A Teensy 3.6 microcontroller with an infrared LED [6] is used to optically program SCμM and calibrate the oscillator frequencies, as depicted in Figure 2. SCμM uses this time reference to tune the 20 MHz CPU clock, the 2 MHz chipping clock, and the 64 MHz IF clock. Notably, the LC oscillator is calibrated later to account for temperature dependence.

B. Solar Cells

The 3.26×3.5 mm^2 Zappy2 CMOS chip contains four high voltage buffers and three solar cell arrays. These arrays supply the internal HV buffer (119 V) and I/O logic (3.5 V) and provide power at $\mathrm{VBATPV} = 1.8\,\mathrm{V}$ to SCμM [9]. The HV buffer has been used in prior configurations to actuate a MEMS gripper [7]. At an irradiation of 200 mW/cm^2 from a bright light, the solar cells provide a short circuit current of 560 μA.

As shown in Figure 3, transmitting a packet (Φ_3) requires a lot of power, so we need to charge the VBAT capacitor between periods of radio operation. Normally, the CPU clock rate is at 5 MHz ($\mathrm{I_{VBAT}} = 380\,\mu\mathrm{A}$) ($\Phi_2, \Phi_4$), but we decrease it to 78 kHz ($\mathrm{I_{VBAT}} = 210\,\mu\mathrm{A}$) ($\Phi_1$) to further reduce SCμM's power consumption in a low-power state. Note that Figure 3 was measured with a 20 μF VBAT capacitor, but a 100 μF one was used for this experiment to improve packet delivery.

Transmitting a packet at 1.6 mA with a duration of 5 ms (Figure 3) requires 8 μC of charge. Assuming a constant VBAT voltage, a 560 μA constant current input from the solar cells at 200 mW/cm^2 irradiation, and a 380 μA idle state between transmissions, the theoretical transmission rate is 30 Hz.

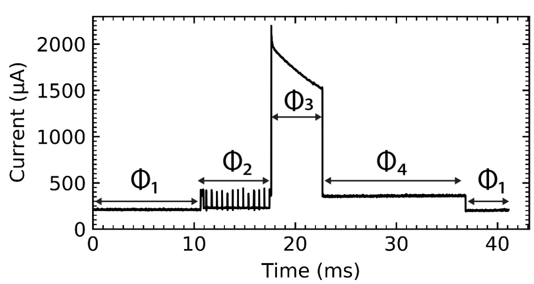

Fig. 3: $\mathrm{I_{VBAT}}$ transient during wireless 802.15.4 transmission (200 mW/cm^2 irradiation; 20 μF capacitor). Φ_1: Low power mode, Cortex clock = 78 kHz, $\mathrm{I_{VBAT}} = 210\,\mu\mathrm{A}$; Φ_2: printf, Cortex clock = 5 MHz; Φ_3: TX, 5 MHz; Φ_4: Configuring back to low power, 5 MHz, $\mathrm{I_{VBAT}} = 380\,\mu\mathrm{A}$

III. System Operation

For this application, SCμM transmits 802.15.4 packets on channel 11 (2.405 GHz). The 802.15.4 specifications prescribe a frequency error less than ±40 ppm. However, since SCμM's oscillators have a large temperature coefficient, it becomes difficult to transmit 802.15.4-compatible packets over temperature variations. In fact, this becomes even more challenging under solar power, which causes the SCμM's supply voltage to vary during packet transmission. In this section, the operational procedure to address to these problems is presented.

A. Optically Program and Calibrate

At 39 °C, SCμM is connected to an external 1.7 V VBAT source due to the sustained high-power radio-on period required during calibration. Once calibrated, a bright light is turned on to provide 200 mW/cm^2 of irradiation, and the power source is disconnected to allow SCμM to operate autonomously, as shown in Figure 2. The illumination is focused solely on the solar cells and does not significantly impact the SCμM temperature measurement.

B. Local Oscillator Temperature Compensation

As a wireless temperature sensing node, SCμM needs to transmit packets at various temperatures. To accomplish this, the RF LO needs to be continually compensated over temperature to stay within approximately ±40 ppm of 2.405 GHz. One prior approach used the frequency error in received packets to compensate the LO over temperature [8]. Further work demonstrated this correction on all sixteen 802.15.4 channels between 5 °C and 55 °C [13]. The LO calibration approach used for this experiment is based on a linear relationship between temperature and the ratio of the temperature-dependent on-chip 2 MHz and 32 kHz clocks [14].

Specifically, the first step for the calibration procedure used for this system involves determining which LC fine codes allow for proper radio transmission at which temperature. As we vary the temperature with a hot plate, we continuously sweep through all 32 LC fine codes, measure the ratio of the on-chip 2 MHz and 32 kHz frequency counts over 100 ms, and transmit the ratio in a 14-byte 802.15.4 packet. The coarse and mid codes were pre-determined from an earlier calibration.

Throughout this process, we record the frequency ratios and LC fine codes of the packets that are successfully received by an OpenMote CC2538 [15]. For each received packet, a reference temperature measurement is taken with a TMP102 digital temperature sensor (±0.5 °C accuracy) attached to a Teensy 3.6 microcontroller. A linear model is then fit between the clock ratio and the LC fine code as shown in Figure 4. For subsequent radio operation, SCμM measures the clock ratio and then use this linear model to determine which LC fine code to transmit at. The viability of this LO temperature compensation is demonstrated by the frequency offsets of the received packets measured by the OpenMote (Figure 5).

C. Temperature Estimate Calibration

Now that SCμM adjusts its LO frequency to properly transmit across different temperatures, the next step is to calibrate SCμM's temperature estimates [14]. This calibration is accomplished by continually transmitting the 2 MHz and

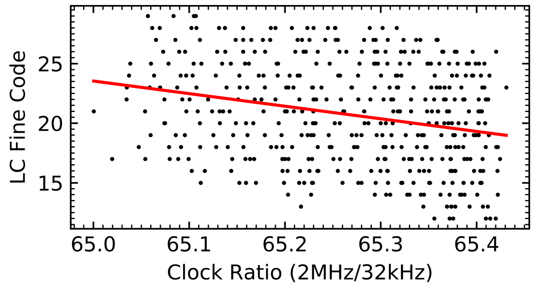

Fig. 4: LC fine codes of packets received by OpenMote (±150 ppm tolerance [12]) and SCµM's 2 MHz/32 kHz ratio

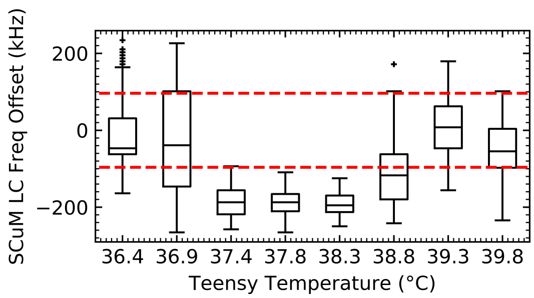

Fig. 5: SCµM frequency error during LC temperature compensation (Lines show ±40 ppm accuracy for 802.15.4 standard).

32 kHz clock ratio to an OpenMote across a temperature range controlled by the hot plate. SCµM continuously corrects its LO frequency using the linear model in Figure 4. Meanwhile, temperature measurements are taken by a TMP102 digital temperature sensor. A linear regression is calculated between the 2 MHz and 32 kHz clock ratio and the reference temperature measured by the Teensy (Figure 6). SCµM then measures the clock ratio and uses this model to produce temperature estimates. This calibration is chip specific.

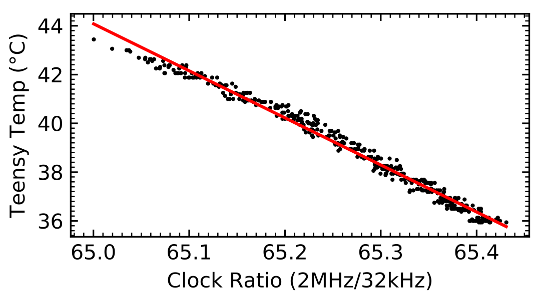

Fig. 6: SCµM temperature estimate calibration

D. Temperature Estimate Operation and Accuracy

SCµM is programmed with the following procedure to test the accuracy of the temperature estimates: 1) Measure 2 MHz and 32 kHz clock counts over 100 ms using the RF timer and compute the ratio. 2) Use the model in Figure 4 to update the LC fine code. 3) Use the model in Figure 6 to estimate the temperature. 4) Decrease the CPU clock rate to 78 kHz for 1 s to charge the VBAT capacitor. 5) Increase the CPU clock up to 5 MHz to transmit a single 10-byte packet containing the temperature estimate. Repeat from step 1.

We show that SCµM can successfully send packets to a ±150 ppm (±360 kHz) tolerant OpenMote CC2538 [12] in a temperature range between 35.5 °C and 40.0 °C. Although some of the packets were outside the ±40 ppm range for 802.15.4 standard as shown in Figure 5, the OpenMote was able to attain a 95.8% packet receive rate across this temperature range. This is what we refer to by standards-compatible. The accuracy of SCµM's temperature estimates is shown in Figures 7 and 8. The standard deviation of the temperature error relative to the Teensy measurement is 0.28 °C.

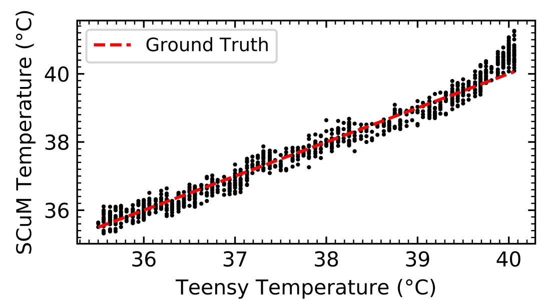

Fig. 7: SCµM's temperature estimate vs. Teensy TMP102 measured temperature

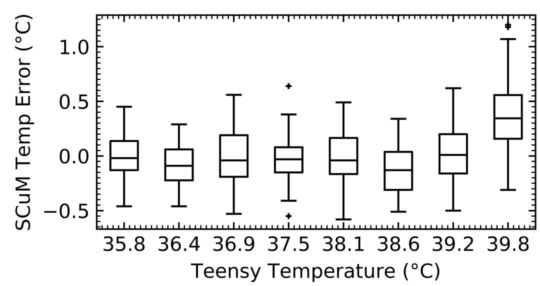

Fig. 8: SCµM's temperature estimate error

IV. Conclusion

An autonomous micro-system that integrates SCµM, Zappy2 and a 100 µF capacitor under 200 mW/cm^2 irradiation was demonstrated to transmit 802.15.4 packets with temperature estimates between 35.5 °C and 40 °C. Specific applications include fire detection and human temperature measurement. Further improvements could be made with a voltage-compensated clock correction using the on-chip ADC. Further integration with MEMS devices will allow this system to function as an RF-controlled autonomous actuator.

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