TI Designs
Matched Precision Temperature Sensing for Heat Cost Allocators

Design Overview

This reference design demonstrates techniques for precision temperature sensing as required by heat cost allocators and other Internet of Things (IoT) applications. Heat cost allocators use the temperature differential between a room and a heating unit to assign a share of the total cost of a central heating system among multiple users. The solution achieves better than a 0.5°C accuracy across a range of 20°C to 85°C. The precision CMOS analog sensors used in the design are available as matched pairs to eliminate the calibration typically required during manufacturing, which lowers the OEM system cost. The design is compliant to the EN834 standard by using the two-sensor measurement method.

Design Resources

TIDA-00646	Tool Folder Containing Design Files
LMT70A	Product Folder
CC1310	Product Folder

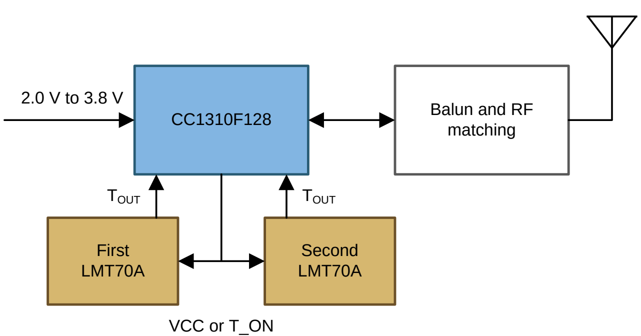
TI E2E™ Community — ASK Our E2E Experts

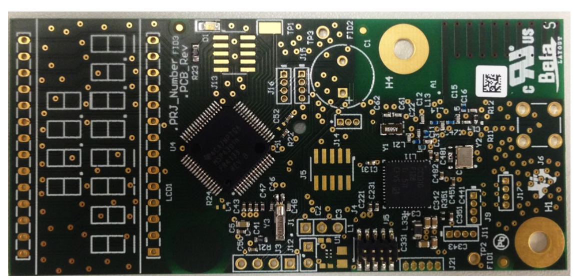
Design Features

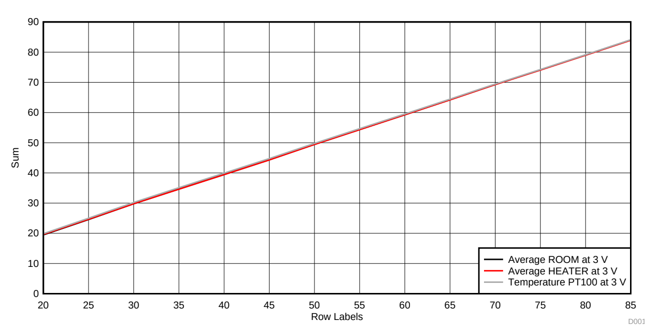
- Highly Accurate Temperature Sensing Across Environment Conditions: Better Than 0.5°C From 20°C to 85°C
- Matching of Two Adjacent LMT70A Sensors on Tape and Reel Lowers Test and Manufacturing Costs
- CC1310 SimpleLink™ Platform Wireless MCU Provides Single-Chip Solution for Heat Measurement and RF Communications
- Low Power Operation Down to 2.0 V Extends Battery Lifetime
- Only 2.56-µA Current Consumption in Active Measurement Once per 4 s
- Cost-Optimized Two-Layer PCB Layout in HCA Form Factor

Featured Applications

- Heat Cost Allocators With w-MBus RF Protocol at 868 MHz up to 15-dBm Transmit Output Power (Compliant to EN834)
- Precision Temperature Sensing With Matched CMOS Sensors in Any Wireless Application
- Internet of Things and Wearable Applications With Precise Temperature Sensing







An IMPORTANT NOTICE at the end of this TI reference design addresses authorized use, intellectual property matters and other important disclaimers and information.

1 Key System Specifications

The CC1310 wireless microcontroller (MCU) operates from 1.8 V to 3.8 V and allows a 3.9-V absolute maximum value.

The LMT70A sensor operates from 2.0 V to 5.5 V and offers temperature matching using CMOS sensors with a 0.1°C maximum at 30°C. The device requires a minimum of 2.1 V for temperatures as low as 0°C; however, 2.0 V is sufficient for 20°C.

Because the heat cost allocators usually start registering at temperatures of 20°C or above, the common supply voltage for this design is from 2.0 V to 3.8 V.

The common operating ambient temperature for a CC1310 and LMT70A is T_A = –40°C to 85°C because of parameters relating to the CC1310; however, the LMT70A has a much wider operating range of −55°C to 150°C.

2 Design Features

Many EU countries now use heat cost allocators (HCAs), which are devices used to accurately bill for heat consumption in houses and apartments. HCAs are a high volume and very cost-sensitive application.

This TIDA-00646 design proposes a subsystem for precise and low-cost temperature measurement suitable for HCAs that meet EN834 requirements. The use of two LMT70A matched temperature sensors eliminates the requirement for calibration at one or two different ambient temperatures, which can be expensive.

This reference design comprises:

- Two LMT70A temperature sensors (matched in production to 0.1°C (maximum) at 30°C
- Wireless system-on-chip (SoC) for a wM-Bus at 868 MHz, which achieves an ETSI category 2 receiver compliance

The CC1310 device directly connects to two LMT70A sensors. Firmware that operates inside the ultralow power sensor controller of the CC1310 controls the LMT70A sensors.

The analog output signal of each LMT70A distributes into a separate CC1310 I/O pin, which is an input to the 12-bit successive approximation register (SAR) ADC converter inside the sensor controller. The CC1310 periodically powers on and enables the LMT70A sensors, after which the ADC12 converter reads the analog input voltage as a digital value. This value is then converted into a temperature value using one of the three possible calculation methods, which are represented by a linear, second-order, or third-order transfer function.

The code example for CC1310 uses the second-order transfer function (or formula) because it is valid for the full temperature range of 20°C to 85°C and beyond.

2.1 *LMT70A—Efficient Synchronous Boost Converter*

The LMT70A is an ultra-small, high-precision, low-power CMOS analog temperature sensor with an output enable pin (see Figure 1). Applications for the LMT70A include virtually any type of temperature sensing where cost effectiveness, high precision, and low power are required, such as Internet of Things (IoT) sensor nodes, medical thermometers, high-precision instrumentation, and battery-powered devices. The LMT70A is also a great replacement for resistance-temperature detectors (RTDs) and precision NTC or PTC thermistors.

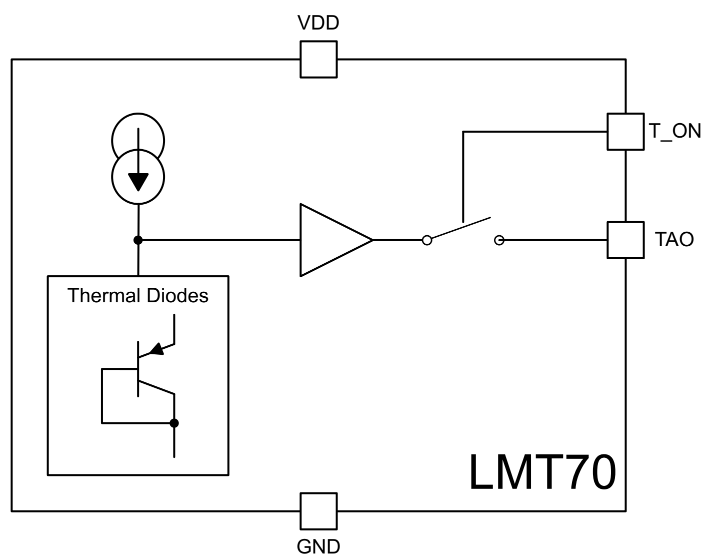


Figure 1. LMT70A Block Diagram

The matching of two LMT70A sensors up to 0.1°C at 30°C is an excellent feature that allows a user to avoid significant effort in temperature calibration and save on the costs during manufacturing.

2.2 CC1310—Wireless MCU for Sub-1-GHz RF Systems

The Cortex-M3 core is the main CPU inside the CC1310 wireless MCU and the sensor controller peripheral of the CC1310 controls the temperature sensing behind the two LMT70A sensors. Figure 2 shows the CC1310 functional block diagram.

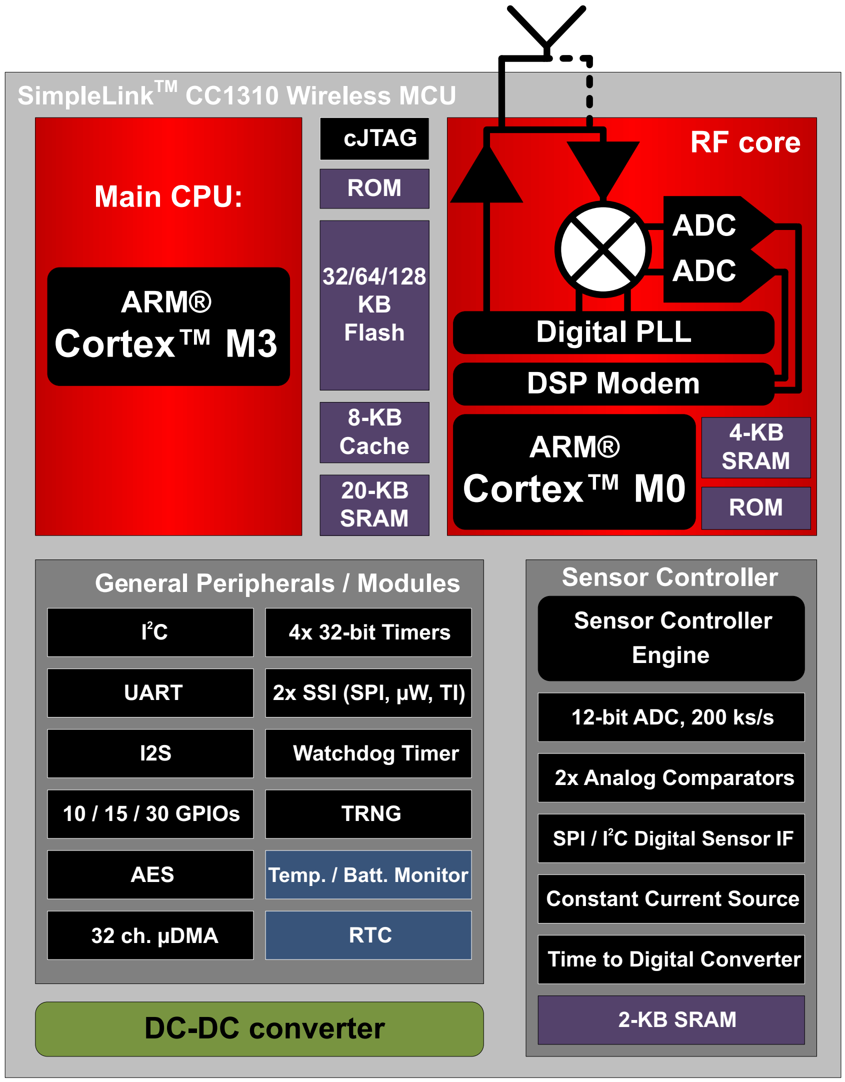


Figure 2. CC1310 Functional Block Diagram

The ARM® Cortex®-M3 runs with up to 48 MHz. The CC1310 device also features 128KB of in-system programmable flash, 8KB of SRAM for cache (or as general-purpose RAM), and 20KB of ultralow leakage SRAM. The ultralow power sensor controller can run autonomously from the rest of the system at 24 MHz and uses only 0.4 mA and 8.2 µA/MHz.

The sensor controller has a 16-bit architecture, which if activated, runs every second to perform a single 12-bit ADC sampling that only consumes 0.85 µA. The sensor controller has a dedicated 2KB of ultralow leakage SRAM for code and data. The CC1310 standby current is 0.6 µA (with RTC running, RAM retention, and Data CPU retention).

Using the sensor controller to seamlessly interface to and read the LMT70A analog output is an innovative approach that delivers excellent, low-power consumption and measurement precision, which makes the controller suitable for heat cost allocators.

The CC1310 device features two calibration values at room temperature (device dependant) for the ADC12, which are for gain and offset respectively.

3 Block Diagram

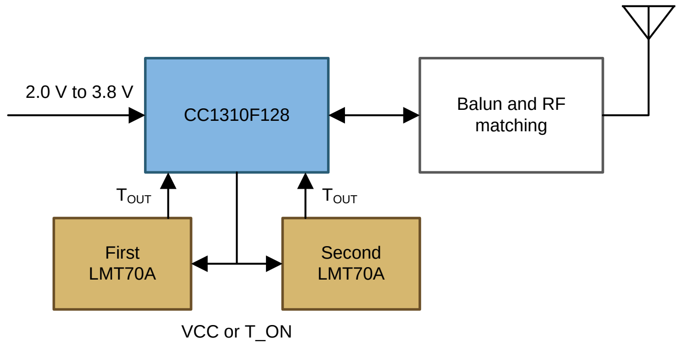


Figure 3. TIDA-00646 Block Diagram

3.1 Highlighted Products

The TIDA-00646 design comprises these main components: The two matched LMT70A temperature sensors and the CC1310 wireless MCU device.

For more information on each of these devices, see the respective product folders at TI.com.

3.1.1 LMT70A—Precision Analog Temperature Sensor

The LMT70A is an ultra-small, high-precision, low-power CMOS analog temperature sensor with an output enable pin. Applications for the LMT70A include virtually any type of temperature sensing that requires cost effectiveness, high precision, and low power, such as Internet of Things (IoT) sensor nodes, medical thermometers, high-precision instrumentation, and battery-powered devices. The LMT70A is also a great replacement for resistance-temperature detectors (RTDs) and precision NTC or PTC thermistors.

The accuracy of the LMT70A is specified as:

- ±0.2°C (maximum) from –20°C to 90°C
- ±0.23°C (maximum) from 90°C to 110°C

The LMT70A provides an unparalleled temperature matching performance of 0.1°C (maximum) at 30°C for two adjacent LMT70As selected from the same tape and reel. The LMT70 also has a linear and low impedance output that allows for seamless interfacing to an off-the-shelf MCU with ADC. Dissipating less than 36 µW, the LMT70 offers ultra-low self-heating to support high precision sensing over a wide temperature range.

These features make the LMT70A an ideal solution for energy metering applications that require heat transfer calculations, such as heat cost allocators.

3.1.2 CC1310—Wireless MCU for Sub-1-GHz RF Systems With Sensor Controller

The CC1310 device contains a Cortex-M3 (CM3) processor and provides a high-performance, low-cost platform that meets the system requirements of minimal memory implementation and low-power consumption while delivering outstanding computational performance and exceptional system response to interrupts.

The sensor controller contains circuitry that can be selectively enabled in standby mode. The peripherals in this domain may be controlled by the sensor controller engine, which is a proprietary, power-optimized CPU. This CPU can read and monitor sensors or perform other tasks autonomously, and significantly reduces the power consumption while offloading the main CM3 CPU.

The SAR ADC module comprises one of the peripherals in the sensor controller. The ADC is a 12-bit, 200-ksamples/s ADC with eight inputs and a built-in voltage reference. The ADC can be triggered by many different sources, including timers, I/O pins, software, the analog comparator, and the RTC.

The analog modules can be connected to up to eight different GPIOs. The peripherals in the sensor controller can also be controlled from the main application processor.

4 System Design Theory

The 12-bit ADC of the CC1310 has two references: A scaled input using a reference of 4.3 V or an unscaled input using a 1.44-V internal voltage reference. The TIDA-00646 uses the 1.44-V internal reference because it covers the full range of the LMT70A sensor with a much higher resolution as compared to the 4.3-V reference. The full range of the LMT70A sensor is approximately 1360 mV at –55°C down to 300 mV for 150°C (see Figure 4).

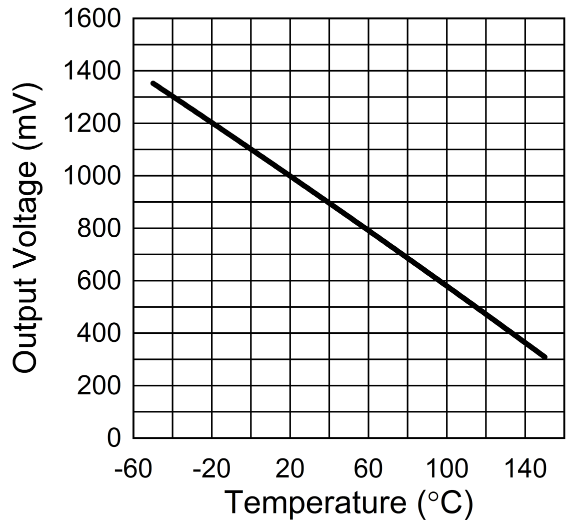


Figure 4. LMT70 Output Transfer Function

The expected analog voltage output of the LMT70 sensors is in the range of 650 mV to 1000 mV for the relevant temperature range of 20°C to 85°C.

4.1 *Connecting LMT70A to 12-Bit ADC of CC1310*

The LMT70A sensor uses a 4-pin DSBGA package, where the supply pin VCC and the output enable pin can be wired together, which saves one I/O pin for each sensor that the design uses. J9 and J11 are used to solder three insulated wires to the heater and room sensors. These heater and room sensors are implemented as a very small PCB with board dimensions of just 2.9 mm × 2.16 mm [8]. Figure 5 shows the layout of this PCB. The top-left via is GND, the next via below is TAO, and the bottom-left via is for both VDD and the output enable pins, which are wired together. The LMT70A is soldered on the back side.

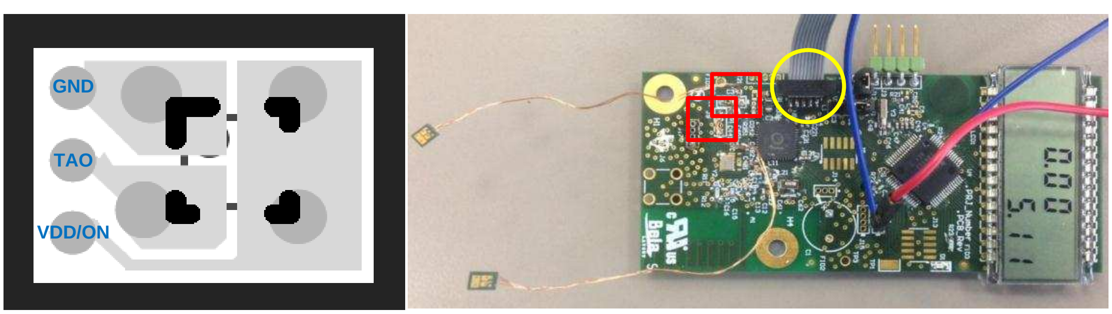


Figure 5. Small PCB Layout for LMT70 (Left) and Two PCBs Soldered to TIDA-00646 (Right)

4.2 Sensor Controller Operation

The sensor controller can perform certain tasks at significantly lower power consumption than the MCU subsystem because of the small size and implementation of the controller in an ultra-low-leakage technology. Some typical use cases where the sensor controller can offload the MCU subsystem are:

- ADC sampling and filtering of results
- Frequency measurements to support oscillator calibration
- Frequency measurements to compensate RTC frequency
- Control of GPIO pins, including bit-banged SPI, I^2C, and universal asynchronous receiver and transmitter (UART)
- Capacitive sensing and filtering of measurement results to reduce load on the system CPU

In this TIDA-00646, the sensor controller provides a periodical readout of the room and heater sensors through the ADC sampling and by calculating the measured temperature. The period itself is software configurable and the user may adapt this to their requirements. The provided software example uses one sample per second for each LMT70A sensor.

5 Getting Started Hardware

To debug the source code on the CC1310 device, the J4 2- × 5-pin connector is used (10-pin ARM JTAG connector). A 10-pin flat ribbon cable interfaces J4 to a SmartRF06 evaluation board with the XDS100v3 Debugger, which is used to program the Cortex-M3 MCU core of the CC1310 (see the yellow circle in Figure 6).

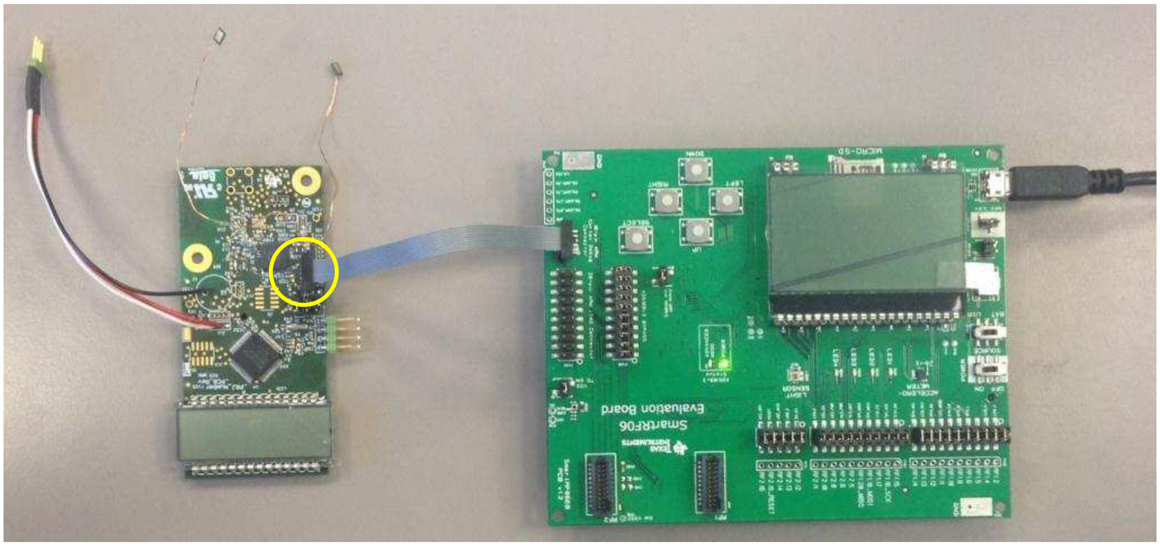


Figure 6. TIDA-00646 Connected to SRF06EB for Power Supply and Debugging

5.1 LMT70A Connection to PCB

The TIDA-00646 PCB does not contain the LMT70A sensors because in HCA applications one temperature sensor measures the heating unit (heater sensor) and the second sensor captures the room temperature (room sensor). All HCA devices are mounted firmly onto the body of the heating unit and the temperature sensor of the heater must make a good thermal contact with the heater surface. In contrast, the room temperature sensor is positioned in the opposite direction to the room or away from the heating unit. The two-sensor approach used in this TI Design is described in the DIN EN834 as the two-sensor measurement method.

The required physical placement of these two sensors makes soldering the LMT70A devices onto the PCB impractical. As a solution, two Jumpers (J9 and J11) with the proper signals for contacting the two sensors are used (see the two red squares in Figure 5).

5.2 UART Link to Terminal Program

A simple UART connection is implemented on the CC1310 device and the RX and TX signals are present at jumper J16. These two signals must be connected to a UART bridged to a virtual COM port converter, an example of which can be found on the MSP430™ MCU LaunchPad from Texas Instruments (TI), MSP430 FET debugger, or SmartRF06EB with port 408, pin 11, and pin 13 (named XDS100v3 BYPASS). With this UART-to-virtual COM port converter, any terminal program can read the UART data from the CC1310 device and write characters back, if the user desires control over the UART function. The default UART settings used for testing are 9600 bps, 8, n, and 1 and the user can modify these UART settings by using the IAR source code project, as required.

6 Getting Started Firmware

A full version of the IAR ARM Embedded Workbench (version 7.40.3 or later) is required to compile and debug the firmware. In addition, the Sensor Controller Studio (SCS), which is a TI provided tool chain, is required to generate the binary code for the sensor controller. Download the SCS software at the following link: http://www.ti.com/tool/sensor-controller-studio [4].

The firmware also requires installation of the TI Real-Time Operating System (TI RTOS) package, which can be installed in the following example pathway: *c:\ti\tirtos_simplelink_2_14_02_22*). The TI RTOS package is integrated with both the IAR Embedded Workbench and TI's Code Composer Studio™ (CCS) IDE tools and can be installed from the integrated development environment (IDE).

Two IAR projects have been provided: *flow_meter.eww* and *flow_meter_uart.eww*. The first project is an ultra-low power version where only the LMT70 reading occurs every second (or at any configurable period). The second project adds UART support such that the LMT70 values transmit to a terminal program on the PC store in a file log for later evaluation.

6.1 Sensor Controller Studio (SCS) Code Project

To ease the development of program code running on the sensor controller, TI provides a complete tool chain to write software for the controller, which is Sensor Controller Studio (SCS), as Figure 7 shows. The SCS is a fully integrated tool consisting of an IDE, compiler, assembler, and linker.

This tool chain can be used to write C-like code for the controller and has a power and event management framework included in the background, which handles most of the complexity regarding the sensor controller and the events and power management. This management framework also handles the complexity that arises in a multi-CPU system, such as the CC1310.

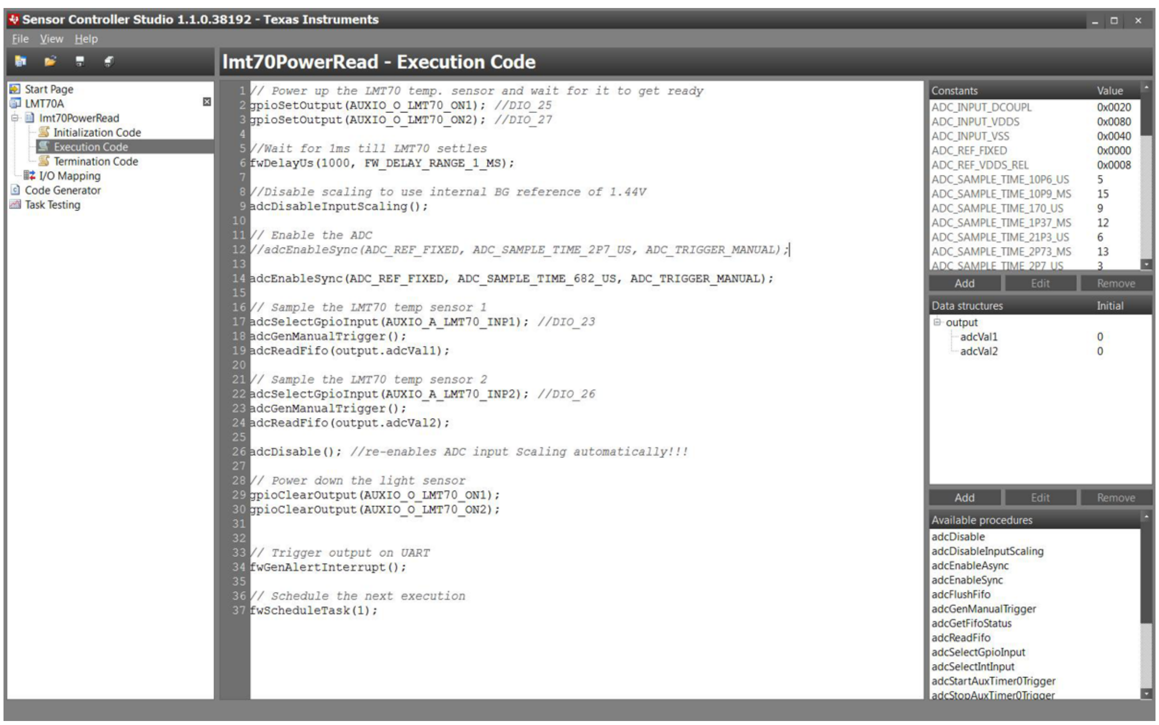


Figure 7. Sensor Controller Project for CC1310 and LMT70A Readout of Each Sensor

6.2 IAR Embedded Workbench for ARM Code Project

The code, which is generated by the SCS project, is a list of files that are part of a bigger IAR project. The IAR main() code example adds the TI RTOS framework and combines the code for the Cortex-M3 core (such as UART functionality) with the sensor controller code into a single firmware image. Figure 8 shows the files that the SCS generates (blue circle).

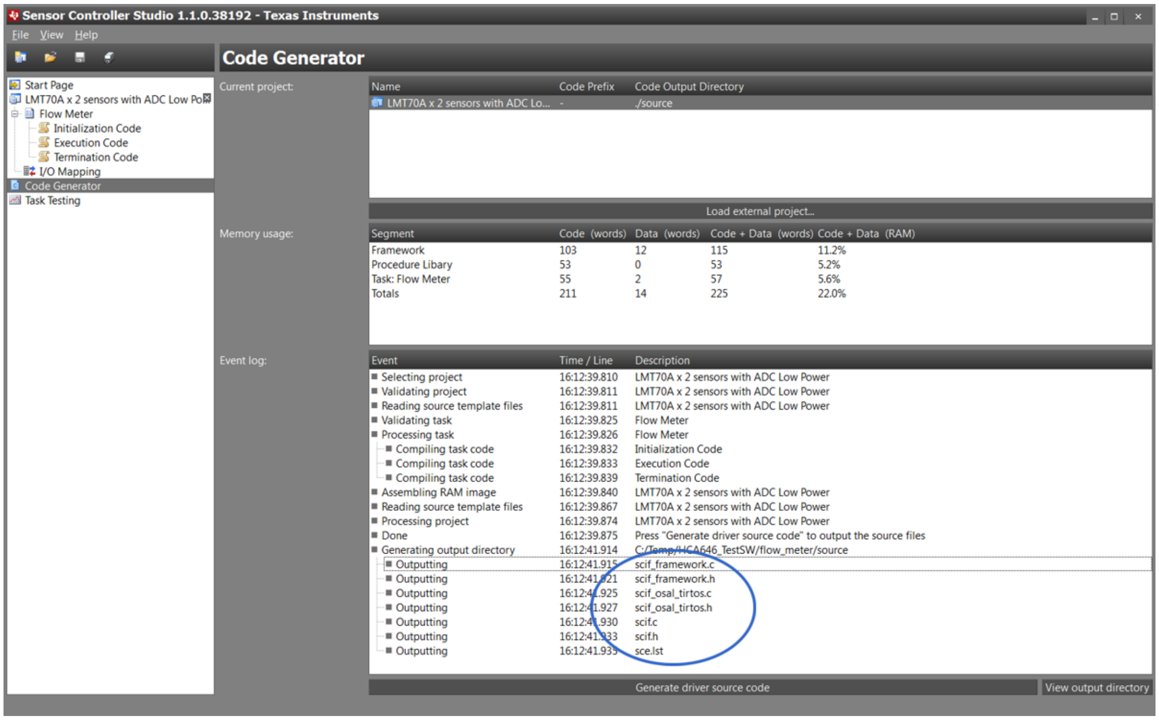


Figure 8. Sensor Controller Ouput Files Included in IAR Project

7 Test Setup

The TIDA-00646 testing is done using SmartRF06 evaluation board as the debugger and virtual COM port hardware. When using the COM port, the user must remove the jumpers on P408 for pins 11 and 12 and pins 13 and 14 on the SmartRF06EB.

The next step in testing is to connect the TX line and RX line of the CC1310 device (J16 on TIDA-00646) through wires to pin 11 and pin 13 respectively, as Figure 9 shows. An important thing to note for the UART connection to work properly is that the MSP430FR4133 (if populated) must be programmed to not drive the UART lines, because these lines are now used for the virtual COM port communication to a Windows PC. Installing the SmartRF™ Studio 7 software also adds the appropriate hardware drivers for the SmartRF06 evaluation board to the PC, including support for the virtual COM port [5].

To capture the Section 8 *Test Data*, the sensor controller project with UART support *flow_meter_uart.eww* was utilized. The current consumption has not been optimized here because the two LMT70 readings are sent out every second over the UART connection using the Cortex-M3 core of the CC1310 device.

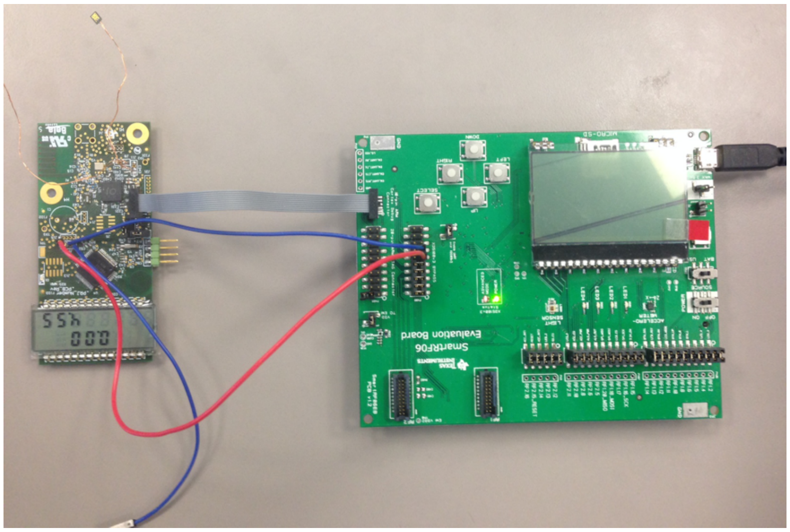


Figure 9. TIDA-00646 With LMT70 Sensors and UART Connection to SmartRF06EB

8 Test Data

Several tests were conducted to characterize the performance of the TIDA-00646 design. The first test uses a temperature oven with a PT100 element inserted as a reference measurement device.

8.1 Temperature Testing Using Temperature Oven

The algorithm for collecting the test data using the temperature oven is:

1. Set the temperature for the oven and wait for it to settle down to 0.3°C (temperatures: 20°C to 85°C in 5K steps).
2. Wait 3600 s.
3. Measure each LMT70A sensor (room and heater) at 2.1 V, 2.5 V, 3.0 V, and 3.6 V once per second for a total of 40 times.
4. Move to the next temperature and start over if the last temperature step has yet to be reached.

The following test results were generated by heating up a temperature oven (or chamber) from 20°C upwards to 85°C (in 5K steps). Figure 10 and Figure 11 show an identical performance for 3.6 V and 3.0 V, which are common battery voltages.

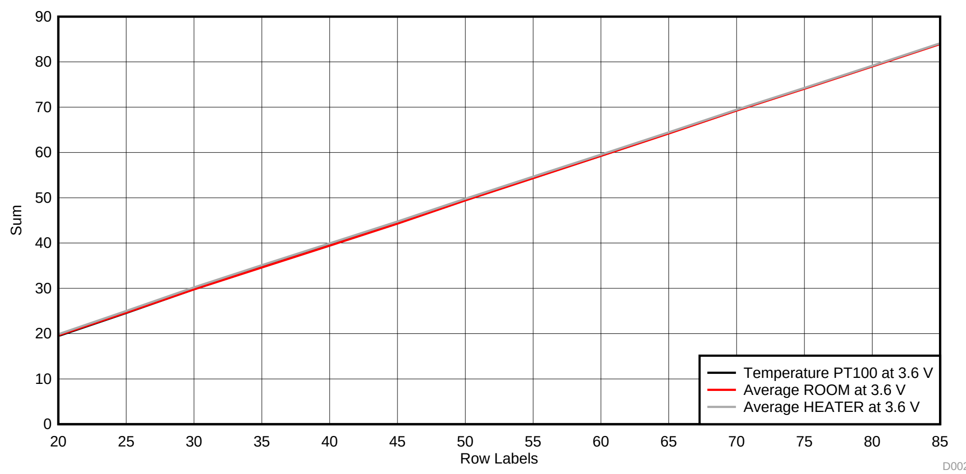


Figure 10. Two LMT70 Sensors (Heating From 25°C to 85°C) at 3.6 V Compared to PT100

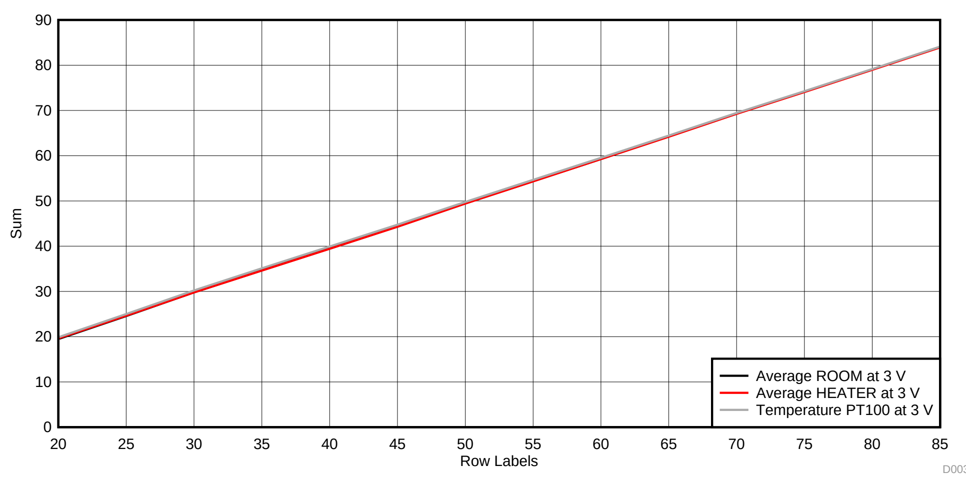


Figure 11. Two LMT70 Sensors (Heating From 25°C to 85°C) at 3.0 V Compared to PT100

The preceding plots used regular or unmatched LMT70 devices (as populated onto the small PCB).

8.2 Temperature Testing Using Precision Oil Bath

A comparison measurement using a different PCB and two LMT70A matched sensors was performed using a precision oil bath (see Figure 12). To enable the correct sampling of the LMT70A output voltage, the sampling time for the ADC12 was extended to 682 µs. The same sampling time was also used when capturing the data in the preceding Figure 10 and Figure 11.

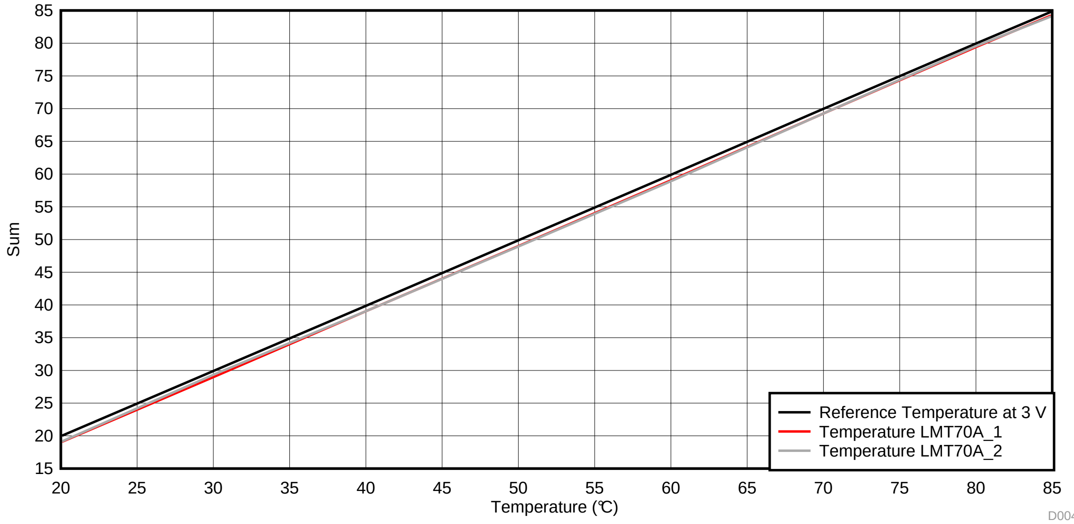


Figure 12. Two LMT70A Sensors in Precision Temperature Oil Bath

8.3 Current Consumption

The current drawn during the temperature sensing for TIDA-00646 was measured using an Agilent N6781A source/measure unit for battery drain analysis. In addition to the CC1310 and two LMT70 sensors on a small PCB, a MSP430FR4133 MCU was populated onto the TIDA-00646 board.

The CC1310 runs the temperature sensing algorithm for reading two LMT70 sensors once per second or once per four seconds. The ADC12 sampling time is set to 682 us. Figure 13 shows the test result at room temperature and with a 3.0-V external supply.

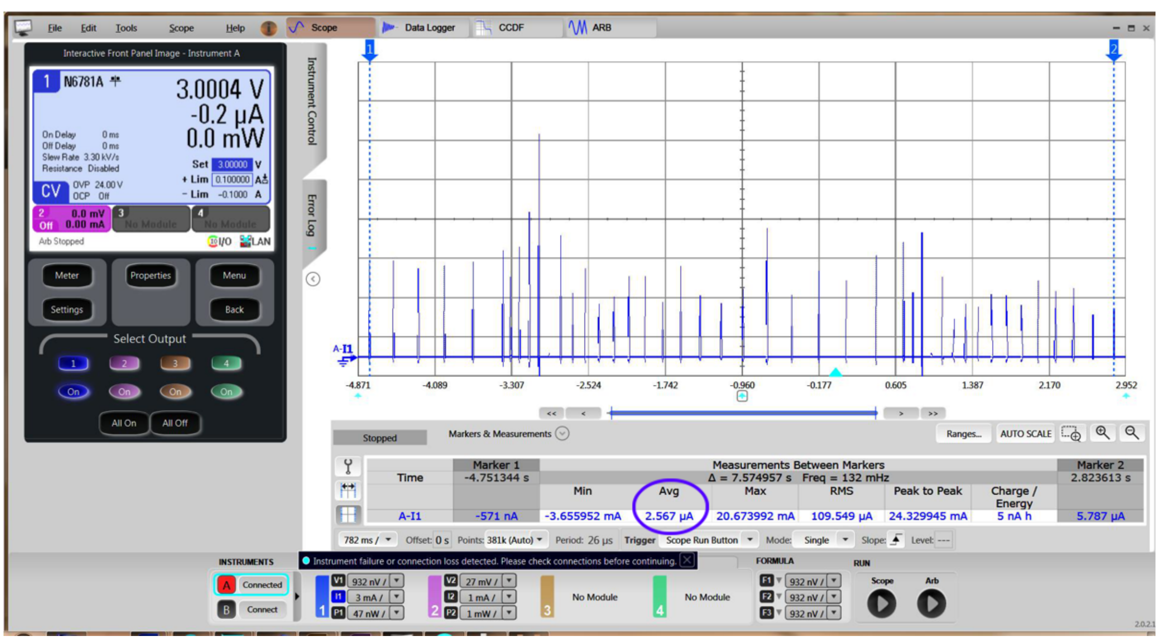


Figure 13. Two LMT70A Sensors Read Out By CC1310 Every Four Seconds

The MSP430FR4133 was programmed with the LPM4.5 code example from the CCS version 6.1.1.00022 IDE tool [9]. In the LPM4.5 state, the MSP430 device operates with only a 15-nA current draw. The integrated LCD controller peripheral was explicitly disabled to save current.

The average current consumption is approximately 2.56 µA at 3 V (see the blue circle in the preceding Figure 13). This plot shows that the current profile is dictated by the DC-DC recharge pulses for the CC1310 on-chip DC-DC controller. UART communication does not occur here and only the periodic LMT70A sensors sample every four seconds.

8.4 Follow-Up—Further Reduction of Current Consumption

To further reduce the current consumption, TI recommends to test and optimize the sampling time for the ADC12 in CC1310. The time 682 µs has been selected with a sufficient margin to allow the ADC12 sampling value to settle. Initial tests at room temperature indicate that this time can be reduced to a much shorter time, for example, 42.6 µs or 85.3 µs. Other measurements show that using the shortest possible sampling time of 2.7 µs introduces a large error.

Another optimization that TI recommends relates to the UART communication with the CC1310 device, where the LMT70A values are reported periodically. Activating the Cortex-M3 core and transmitting very few bytes every few seconds at 9.6 kbps is quite inefficient. A possible alternative is to collect the temperature values in a buffer inside the 2-KB RAM memory of the sensor controller. The sensor controller task only requires 452 bytes , leaving almost 1600 bytes free for buffering data. The buffered data must be transferred in bursts of a few hundred bytes to avoid power-down sequences and activating the M3-core too frequently.

Increasing the UART data rate to 230.6 kbps or 460.8k bps also reduces the average data consumption of the CC1310 device because of a shorter active time for the Cortex-M3 core and the UART peripheral.

9 Design Files

9.1 Schematics

To download the schematics for each board, see the design files at TIDA-00646.

9.2 Bill of Materials

To download the bill of materials (BOM) for each board, see the design files at TIDA-00646.

9.3 PCB Layout Recommendations

The TIDA-00646 design consists of a two-layer PCB with an approximate 1-mm overall thickness. The two layers lower the cost of the design while the 1-mm thickness increases the mechanical stability of the PCB. The layout follows the exact CC1310 reference design as specified in the CC1310 design files [2].

9.3.1 Layout Prints

To download the layout prints for each board, see the design files at TIDA-00646.

9.4 Altium Project

To download the Altium project files for each board, see the design files at TIDA-00646.

9.5 Gerber Files

To download the Gerber files for each board, see the design files at TIDA-00646.

9.6 Assembly Drawings

To download the assembly drawings for each board, see the design files at TIDA-00646.

10 Software Files

To download the software files for this reference design, see the design files at TIDA-00646.

11 References

1. Beuth.de, *Heat cost allocators for the determination of the consumption of room heating radiators - Appliances with electrical energy supply*, DIN EN 834:2013-12 Standard (http://www.beuth.de/en/standard/din-en-834/190493004)
2. Texas Instruments, SimpleLink CC1310 2-Layer 7×7 Differential 779-930 MHz v1.3.3 Design Files (http://www.ti.com/lit/zip/swrc309)
3. Texas Instruments, *CC1310 SimpleLink™ Ultralow Power Sub-1-GHz Wireless MCU*, CC1310 Data Sheet (SWRS181)
4. Texas Instruments, *Sensor Controller Studio* (http://www.ti.com/tool/sensor-controller-studio)
5. Texas Instruments, *SmartRF Studio* (http://www.ti.com/tool/smartrftm-studio)
6. Texas Instruments, *LMT70, LMT70A ±0.05°C Precision Analog Temperature Sensor, RTD and Precision NTC Thermistor IC*, LMT70 and LMT70A Data Sheet (SWRS181)
7. Texas Instruments, *LMT70EVM BoosterPack*, LMT70EVM BoosterPack User's Guide (SNIU024)
8. Texas Instruments, *Wearable Temperature Sensing Layout Considerations Optimized for Thermal Response*, LMT70 Application Report (SNIA021)
9. Texas Instruments, *Code Composer Studio (CCS) Integrated Development Environment (IDE)* (http://www.ti.com/tool/ccstudio)

12 Terminology

CCS— Code Composer Studio™ software from TI

ETSI Category 2 Receiver— Definition for a set of RF parameters in EN300 220 v2.4.1, representing the minimum requirement in wM-Bus capable RF systems at 868 MHz

HCA— Heat cost allocators: battery–powered electronic devices used to capture the proportionate thermal output of radiators in consumer units

Heater sensor— Temperature sensor, attached to the radiator (or heating element)

NTC— Negative temperature coefficient

PTC— Positive temperature coefficient

Room sensor— Temperature sensor for monitoring the room or ambient air temperature

RTD— Resistance-temperature detector

SCS— Sensor Controller Studio tool from TI

TI RTOS— Texas Instruments Real-Time Operating System

13 About the Author

MILEN STEFANOV (M.Sc.E.E) is a System Engineer at TI, working in the field of Grid Infrastructure and an expert in RF communication technologies and Metering applications. After graduating, he spent 5 years as a research assistant at University of Chemnitz (TUC) and 3.5 years in the semiconductor industry in high-speed optical and wired communications as a system engineer. He joined TI in 2003 to become a Wi-Fi expert and support TI's Wi-Fi products at major OEMs; since 2010 he is focusing on Metering and Sub-1-GHz RF solutions for the European grid infrastructure market. Mr. Stefanov has published multiple articles on wM-Bus technology in Europe and presented technical papers at the Wireless Congress and SmartHome & Metering summits in Munich.