TI Designs
Reference Design for Segment LCD Control Using GPIO Pins to Increase System Flexibility

TI Designs

Seven-segment LCDs are very popular in ultra-low power metering and submetering applications such as heat cost allocators, water, and heat meters and are typically controlled by a dedicated on-chip LCD controller module in the MCU. This design shows an alternative, patent-pending solution that can be used with any TI MCU without such an on-chip module. Using a few resistors and GPIO control software, the LCD drive functionality has been implemented on a CC1310 Wireless MCU. This design shows how to add LCD functionality to any application, where LCD is required but does not have to be always on. The LCD itself is switched-off most of the time and only enabled when required. The available GPIO lines of the wireless MCU are the limiting factor for the number of LCD segments that can be supported.

Design Resources

TIDA-00848	Design Folder
CC1310	Product Folder
LMT70A	Product Folder
TIDA-00646	Tools Folder

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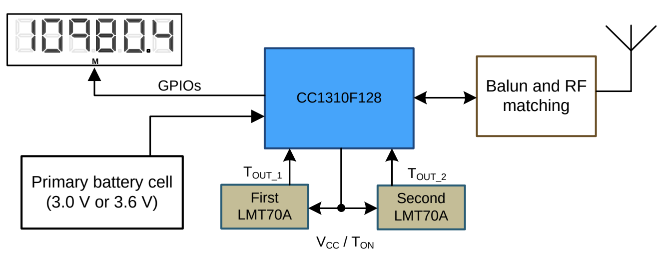

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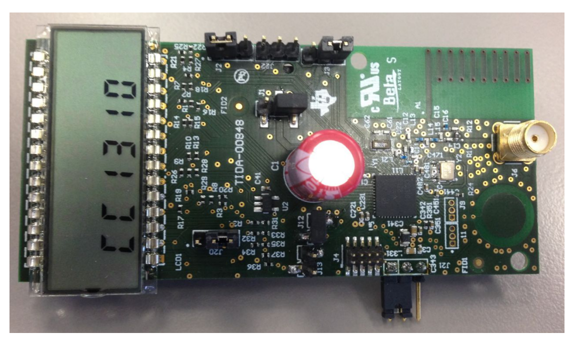
Design Features

- CC1310 SimpleLink™ Wireless MCU Controls Seven-Segment LCD Through GPIOs (Patent Pending Solution)
- Only 4 COM, 2 Control, and 20 Segment Lines (26 I/Os total) Needed to Drive 80 LCD Segments (4-MUX, 1/3-Biasing)
- Sensor Controller Peripheral Senses the Capacitive Touch PCB Area and Reads Out the LMT70A Sensors Periodically
- Two-Layer PCB With HCA Form Factor Using a 96-Segment LCD (4-MUX) and Cap Touch Area for LCD On/Off
- Average Current: 835 nA at 3.6 V (LCD Off); 338 µA at 3.6 V (80 LCD Segments On)

Featured Applications

- Any Metering and Submetering Subsystems With Segment LCD Functionality Using TI MCUs Without On-Chip LCD Controller
- Sub-1GHz RF Enabled Subsystems for 433- or 868-MHz Bands With TI MCUs and Seven-Segment LCD
- Internet of Things (IoT) Applications With TI MCUs and Seven-Segment LCD



1 Key System Specifications

The CC1310 Wireless MCU operates from 1.8 to 3.8 V (3.9 V is the absolute maximum value allowed).

The LMT70A operates from 2.0 to 5.5 V (the matched CMOS temperature sensors with 0.1°C (max) at 30°C); a minimum of 2.1 V is required for temperatures down to 0°C while 2.0 V is sufficient for 20°C.

As heat cost allocators (HCAs) start registering at temperatures of 20°C or above, the common supply voltage for the TIDA-00848 is from 2.0 to 3.8 V. This is a very nice fit for primary battery chemistries, which are either 3.6 V or 3.0 V nominal.

The operating ambient temperature for CC1310 33 is T_A = –40°C to 85°C while LMT70A has a wider operating range of T_A = −55°C to 150°C.

2 System Description

Many low-cost metering and submetering applications require seven-segment LCD functionality, due to the very low-power, low cost and small size of these displays. All these LCD-based applications can either have the LCD always on or can tolerate the temporarily deactivation of the LCD to save power. Water and heat meters as well as HCAs products, which have been already deployed in the field, can be assigned to either of these two categories.

Sometimes, based on country specific regulations, the LCD functionality may be required to be always on. If so, then the on-chip LCD controller module in the MCU for lowest power consumption is a must have.

The alternative approach is to have a solution that enables users to read the LCD whenever they like to; for the majority of the time, while no one reads the display, the LCD functionality will be disabled to save power. For this latter application, the TIDA-00848 proposes an innovative and TI patent pending solution for software controlled GPIOs driving seven-segment LCDs.

NOTE: This patent-pending solution can only be used "free of charge" in combination with MCU products by Texas Instruments Inc., such as the CC13xx, the CC26xx, or MSP43x product families.

The TIDA-00848 represents a single-chip HCA design reference design for wM-Bus at 868-MHz enabled HCAs, meeting these EN834 requirements:

- Two LMT70A temperature sensors, matched in production to 0.1°C (max) at 30°C
- CC1310 Wireless SoC for wM-Bus at 868 MHz RF subsystem with S-, T-, and C-modes

The TIDA-00848 drives the LCD seven-segment display through a dedicated external resistor network (see Section 9.1) and special software, provided as an open-source example. The CC1310's sensor controller peripheral is directly connected to two LMT70A sensors, which are periodically enabled to measure temperature; otherwise, the sensors are powered down. In parallel, the sensor controller checks every second for a PCB touch event. If it detect an event, the LCD functionality is enabled and the LCD will from now on periodically be enabled and disabled. When enabled, the LCD alternates between showing the string "CC1310" and switching on all supported 80 segments.

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

The CC1310 Wireless MCU has an ARM® Cortex™-M3 core for application development (see Figure 1).

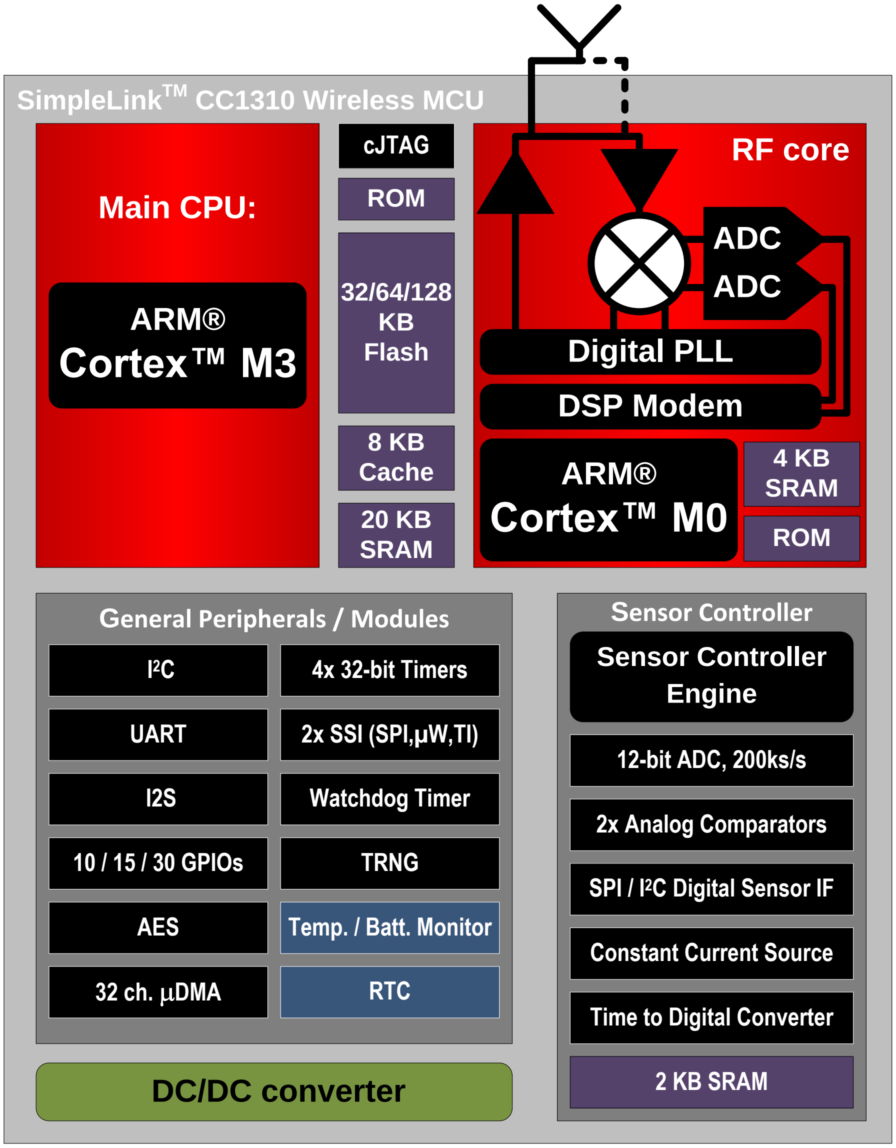


Figure 1. CC1310 Functional Block Diagram

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

The sensor controller has a 16-bit architecture, controls the 12-bit ADC hardware block, and has its dedicated 2KB of ultralow leakage SRAM for code and data. The CC1310 standby current is 0.6 µA (with RTC running and RAM and data CPU retention). The sensor controller seamlessly interfaces to and reads the LMT70A sensors and the capacitive touch PCB area to deliver outstanding low-power consumption with very good precision, suited for HCAs as per EN834. The CC1310 comes with two calibrations values at room temperature for the ADC12: one for gain and one for offset.

2.2 LMT70A—Matched Precision CMOS Temperature Sensor With Analog Output

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 where cost effectiveness, high precision, and low power are required, such as IoT sensor nodes, medical thermometers, high-precision instrumentation, and battery-powered devices. The LMT70A is also a great replacement for RTD and precision NTC and PTC thermistors.

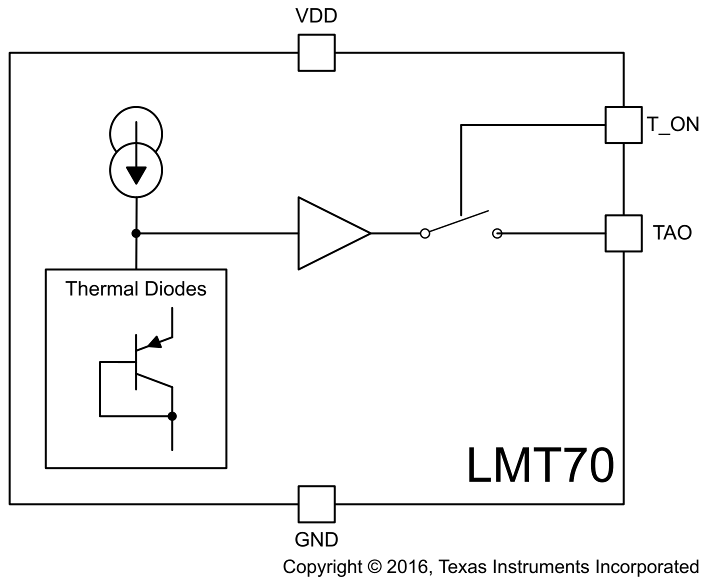


Figure 2. Block Diagram of LMT70A

The matching of two LMT70A up to 0.1°C is a unique feature, saving significant calibration effort and time during manufacturing, thus lowering the total cost of the HCA product.

3 System Design Theory

HCAs are expected to start measuring at temperature of 20°C or higher, the maximum supported temperature is usually 85°C or 90°C. The analog voltage output of the LMT70A for this temperature range will be approximately between 600 mV to 1 V, as shown in Figure 3 for the LMT70 sensor output signal specification.

For RF-enabled subsystems, an MCU + RF transmitter (or transceiver) is required or an integrated RF capable device such as the CC1310 SimpleLink Wireless MCU. As the CC1310 has no on-chip LCD controller module, the TI patent-pending solution presented here has been developed and tested.

3.1 Wireless MCU CC1310

The CC1310's 12-bit ADC has two references: a scaled input for a scaled reference of 4.3 V or an unscaled input using a 1.44-V internal voltage reference. The 1.44-V reference was selected here due to its higher resolution coverage of the full range of approximately 1360 mV at –55°C down to 300 mV at 150°C of the LMT70A sensors.

In this TI Design, the sensor controller periodically reads out both the room and heater sensors through sampling the ADC12 input signals and converting the two LMT70A voltages measured into temperature values. The readout period is software configurable by the user; the provided firmware example project for the sensor controller sets a read-out every four seconds for each LMT70A sensor (as described in detail in the TIDA-00646 design guide [3]).

The sensor controller example project additionally supports a second concurrent task, which checks the PCB capacitive touch area every second (this period is also software configurable by the user). A round PCB area to detect capacitive touch has been integrated onto the TIDA-00848 PCB and is connected to the sensor controller of the CC1310. The CC1310 runs the main application under TI RTOS.

3.2 LMT70A—Precision Analog Temperature Sensor

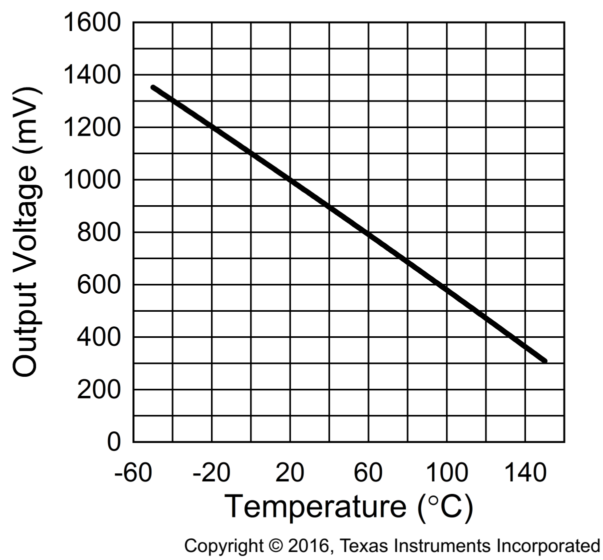


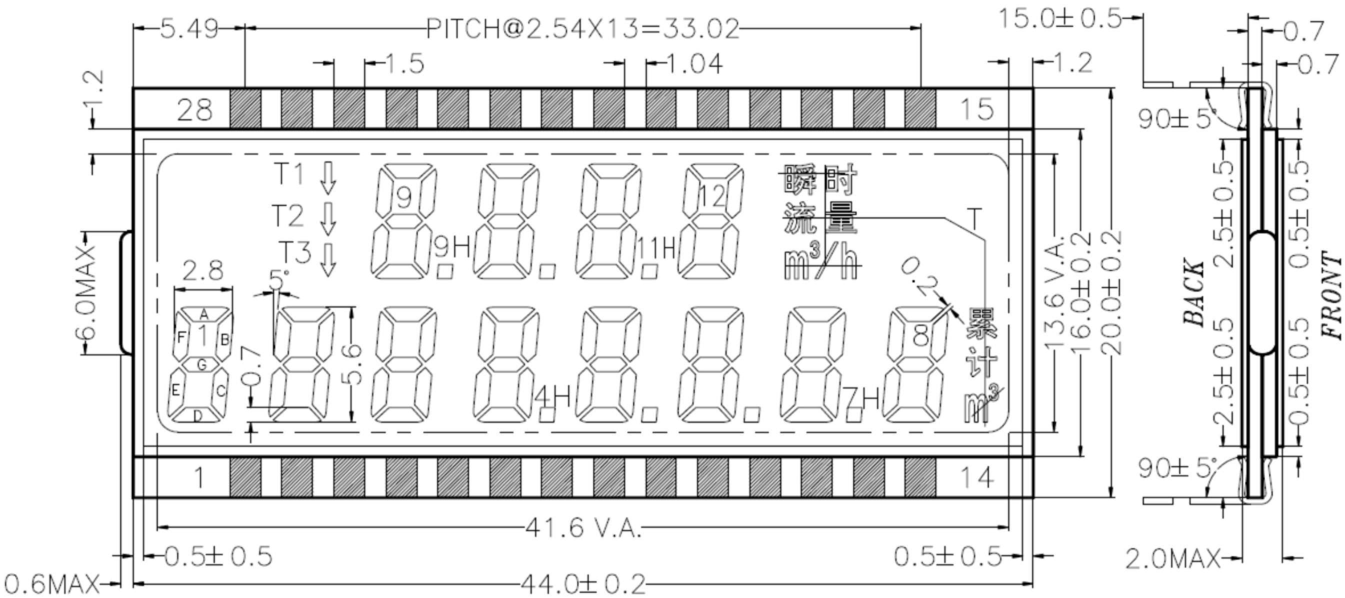
Figure 3. LMT70 Output Transfer Function

The LMT70A output voltage across the temperature range is documented in the device's datasheet (SNIS187) and shown in Figure 3. As the maximum output voltage is always below 1.4 V, it is necessary to disable the voltage scaling inside the ADC12 to achieve higher resolution when sampling the LMT70A analog voltage.

3.3 4-MUX 1/3 Biasing Seven-Segment LCD With 96 Segments

The LCD BTL002 with 96 segments and 4-MUX capability was chosen due to its small physical dimensions and low-power consumption.

The specification of the LCD is given in Figure 4:



PIN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
COM1	1A	1F	2A	2F	3A	3F	4A	4F	5A	5F	6A	6F	7A	7F	8A	8F	9A	9F	10A	10F	11A	11F	12A	12F	COM1	--	--	--
COM2	1B	1G	2B	2G	3B	3G	4B	4G	5B	5G	6B	6G	7B	7G	8B	8G	9B	9G	10B	10G	11B	11G	12B	12G	--	COM2	--	--
COM3	1C	1E	2C	2E	3C	3E	4C	4E	5C	5E	6C	6E	7C	7E	8C	8E	9C	9E	10C	10E	11C	11E	12C	12E	--	--	COM3	--
COM4	T1	1D	T2	2D	T3	3D	4H	4D	5H	5D	6H	6D	7H	7D	T	8D	9H	9D	10H	10D	11H	11D	--	12D	--	--	--	COM4

Figure 4. BTL002 Specification (96-Segment LCD)

3.4 Seven-Segment LCD GPIO Solution Description (TI Patent Pending)

The biasing value of any LCD defines how many intermediate voltage levels the LCD supply voltage (V_{LCD}) is divided into. For example, the 1/3 biasing of the BTL002 display means there are four different voltage levels: 0 V_{LCD}; 1/3 V_{LCD}; 2/3 V_{LCD}; and 3/3 V_{LCD}. These four levels correspond to V5, V4, V2, and V1 in Figure 5.

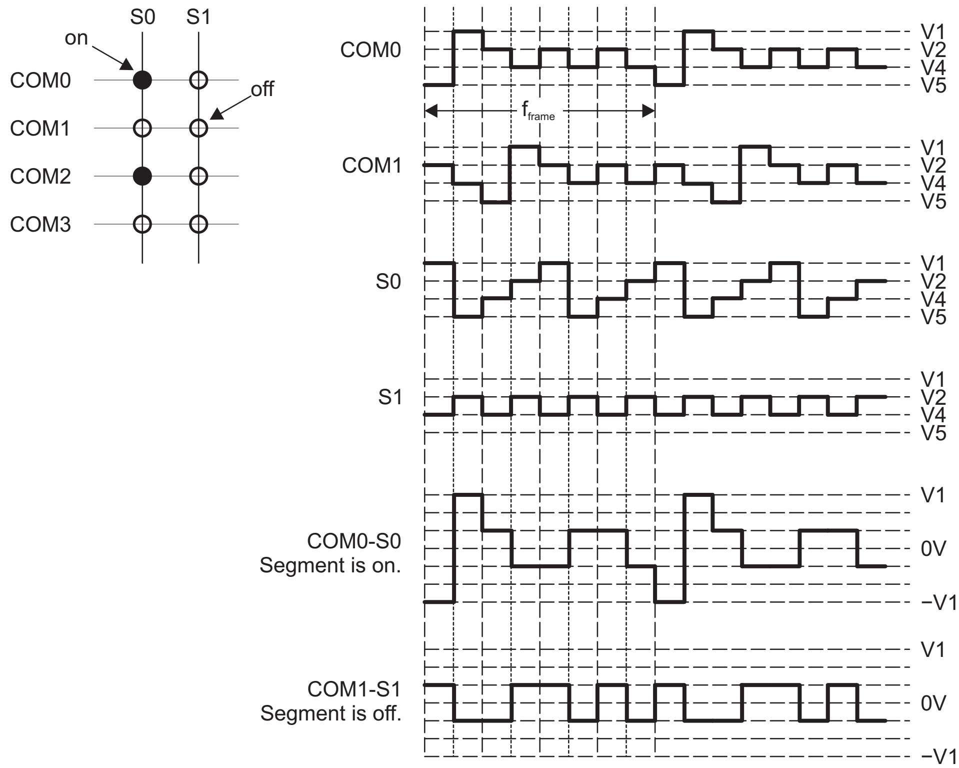


Figure 5. COM0/COM1 and SEG0/SEG1 Example Waveforms for Any 4-MUX LCD

3.5 Generating Square LCD Waveforms Through GPIOs (TI Patent Pending)

Problem: How can one generate a square wave signal, toggling between 2/3 V_{LCD} and 1/3 V_{LCD} by only using logic signals, which toggle between V_{LCD} and GND?

The TI patent-pending solution provides an intelligent way to generate the intermediate LCD voltage levels of 1/3 V_{LCD} and 2/3 V_{LCD} by using a resistive network, a single inverter and the superposition of the COM signals with an auxiliary clock signal, BASE_PWM. The second option of the TI patent pending solution defines that the inverter function is replaced thru another GPIO signal, called BASE_PWM_N.

In contrary to a PWM-based GPIO approach, existing today, the number of external components of the TI solution is less. Only resistors and the optional single inverter are required. On the firmware side, no high-speed complex signals are required. Just a simple timer tick based switching of IOs at a rate of 1/8 of the LCD frame frequency is needed. This reduces the necessary resources on the MCU and thus also the current consumption significantly, compared to a PWM-based GPIO LCD solution.

3.5.1 COM Lines Generation

The square waveforms in Figure 5 can be generated using one additional signal, called BASE_PWM, and its inverted version, named BASE_PWM_N, with the help of resistor divider networks, see R30-R38, with 100 kΩ and 200 kΩ, respectively. In addition, the R28 and R29 resistor divider again uses this 1/3-to-2/3 ratio, but the resistor values are 33.2 kΩ and 66.5 kΩ. The reason is that the current flowing through the SEG_BASE_COMMON will at worst be shared by the 20 segment lines, when all 80 LCD segments are on.

While the operation of the SN74AHC inverter has been tested successfully, a significant drawback of continuous extra current flowing through the resistor network R28 and R29 was identified. Thus, the final implementation (optimized for lower power consumption) removed the inverter and repurposed the DIO_9 pin of the CC1310 as the BASE_PWM_N signal, which is simply the inverted version of the BASE_PWM. By setting the DIO_9 or BASE_PWM_N to output low state while the LCD is inactive, the current through R28 and R29 is eliminated.

The COM and segment electrodes form at their intersection a capacitor, with the liquid crystal as dielectric matter in between them. In a 4-MUX display, one LCD segment pin is internally connected to 4 (or fewer) segments: pin segment 1 (S1) of the BTL002 connects to the 1A, 1B, 1C, and T1 segments on the display—see the left column for Pin1 in Figure 4. Note that and each of these segments connects to a different COM plane (COM line) to enable a time multiplexing control of each segment.

The required voltage to drive a segment LCD device has to be DC free in respect to 0 V_{LCD}, thus after driving the common plane (COM signal) a second phase is needed with the reversed polarity, see *Technical Information and Application Notes* [10].

Thus for the BTL002 display, there must be 4 COM × 2 = 8 sub-divisions in every single frame sent to the LCD. This is shown in Figure 5 for the COM0 line with the f_{frame} period; the frame rate is commonly selected between 30 frames per second (fps) for flicker-free LCD viewing and maximum of 60 to 90 Hz to keep current consumption at a reasonable value.

In the TIDA-00848 source code project, the following definitions have been made:

- Two BASE_PWMx and four COMy lines to generate the proper waveforms with minimum MCU effort
- Eight subphases (one for driving the COM plane and segments; the next is a reversed polarity for DC free control of the LCD)
- Segment lines need to be dynamically tri-stated, or set to output HIGH or LOW for each subphase

Based on the schematics and the BTL002 specification in Figure 4:

Table 1. Output Signals for COM1_1 Through COM1_4, BASE_PWM, and BASE_PWM_N at CC1310

SIGNAL	GPIO NUMBER	HEX VALUE (BIT 31 TO BIT 0)
Base_PWM_N	DIO_9	0000 0000 0000 0000 0000 00X0 0000 0000
Base_PWM	DIO_26	0000 0X00 0000 0000 0000 0000 0000 0000
COM1_1	DIO_22	0000 0000 0X00 0000 0000 0000 0000 0000
COM2_1	DIO_23	0000 0000 X000 0000 0000 0000 0000 0000
COM3_1	DIO_24	0000 000X 0000 0000 0000 0000 0000 0000
COM4_1	DIO_25	0000 00X0 0000 0000 0000 0000 0000 0000

Definitions:

- The two BASE_PWMx lines and the four COMy lines are always configured as the output. The COM1_1, COM2_1, COM3_1, and COM4_1 lines use the same waveform for each f_{frame} period This basic waveform gets delayed by two subphases for the next COM line - Figure 5 shows this for COM1 and COM2 (COM0 starts at 0 V, COM1 is at 0 V after two subphases).
- BASE_PWM is actually a simple 0, 1, 0, 1…(HIGH-LOW) periodic pulse signal; BASE_PWM_N is the opposite (or 180 degrees delayed version) of BASE_PWM.

The eight subphases are numbered with the State0 through State14 (even numbers); thus, the name of first subphase is lcdCOMState0.

Beginning with COM1_1 at 0 VLCD (equals COM0 in Figure 5) in the first subphase: the BASE_PWM signal has to be 0, because according to Figure 5 this is 0 V (outmost left or first subphase for COM0). The combination of COM1_1 and BASE_PWM signals delivers the signal for COM1, which is then applied to the BTL002 LCD device.

As BASE_PWM is 0, then BASE_PWM_N is by definition 1 (inverted BASE_PWM). The COM2_1, COM3_1, and COM4_1 lines are then 1. The State2 then inverts all BASE_PWMx and COMy signals in State 0.

In State 4, the COM2_1 (equals COM1 in Figure 5) should be 0 together with BASE_PWM while COM1_1, COM3_1, and COM4_1 are non-zero, means 1. State 6 is then inverting of all BASE_PWMx and COMy signals in State4.

In State 8, the COM3_1 is set to 0 together with BASE_PWM while COM1_1, COM2_1, and COM4_1 are non-zero, means 1. State 10 reverses the polarity of the relevant bits.

Finally in State 12, the COM4_1 is set to 0 together with BASE_PWM while COM1_1, COM2_1, and COM3_1 are non-zero, means 1. State 14 reverses the polarity of the relevant bits.

Due to these considerations, the resulting values for the COMy and BASE_PWMx lines are:

Table 2. Output Signals for COM1_1 Through COM1_4, BASE_PWM, and BASE_PWM_N

LINE	VALUE
lcdCOMState0 =	0000 0011 1000 0000 0000 0010 0000 0000 = 0x0380 0200
lcdCOMState2 =	0000 0100 0100 0000 0000 0000 0000 0000 = 0x0440 0000 (reversing polarity of lcdCOMState0 of COMy and Base_PWMx lines for DC free)
lcdCOMState4 =	0000 0011 0100 0000 0000 0010 0000 0000 = 0x0340 0200
lcdCOMState6 =	0000 0100 1000 0000 0000 0000 0000 0000 = 0x0480 0000 (reversing polarity of lcdCOMState4 of COMy and Base_PWMx lines for DC free)
lcdCOMState8 =	0000 0010 1100 0000 0000 0010 0000 0000 = 0x02C0 0200
lcdCOMState10 =	0000 0101 0000 0000 0000 0000 0000 0000 = 0x0500 0000 (reversing polarity of lcdCOMState8 of COMy and Base_PWMx lines for DC free)
lcdCOMState12 =	0000 0001 1100 0000 0000 0010 0000 0000 = 0x01C0 0200
lcdCOMState14 =	0000 0110 0000 0000 0000 0000 0000 0000 = 0x0600 0000 (reversing polarity of lcdCOMState12 of COMy and Base_PWMx lines for DC free)

The hex values in Table 2 are the ones programmed in the source code LCD HeartBeatFxn() function for each subphase for the COMy and BASE_PWMx signals.

3.5.1.1 Segment Lines

In TIDA-00848, the segment lines between CC1310 and BTL002 correspond to DIO_1 (DIO_0 is not available) through DIO_21, or in hex value these GPIO bits are equal to 0x003FFFFE.

The DIO_9 line is in fact no more a segment signal but to keep things common regardless if external Inverter is used or not, this value can stay as is. The port functions in the CC1310 will apply the values automatically only to the GPIOs that are allocated.

In the example source code, DIO_9 is assigned to the BASE_PWM_N and is not controlled by the segments structure.

3.5.2 Segment Line Generation

To generate the appropriate segment line waveforms for the LCD one has to set the corresponding MCU GPIO pins either in tri-state (for "segment off"), or in the two output states HIGH/LOW, in case of "segment on". The full amplitude is the result of the differential voltage between segment and COM lines at the LCD pins.

To enable the generation of these segment waveforms, a common support signal, named SEG_BASE_COM signal has been defined. This SEG_BASE_COM signal delivers a simple pulse sequence with the same eight subphase timing and switching between the values of 1/3 and 2/3 VLCD.

With that, now one can calculate the segment values for the desired LCD display string; here, the character string "CC1310" is analyzed.

For simplification, only the first "C" character is explained. The top-left column in Table 3 shows the "CC1310" characters to display in the BTL002 digits 2, 3, 4, 5, 6, and 7. Then, the first "C" (highlighted in red) will be in BTL002 digit 2 and requires segments 2A, 2F, 2E, and 2D to be enabled for the character "C" to become visible on the LCD.

For the second "C", segments 3A, 3F, 3E, and 3D have to be enabled; this also applies for the characters "1", "3", "1", and "0".

Table 3. Displaying the String "CC1310" With All Signals Required (COMx and SEGy)

CHARACTER	SEGMENT	SIGNAL			
C	**2A, 2F, 2E, 2D**	COM1		COM2	
C	3A, 3F, 3E, 3D	0x0000 4000	2A	0x0000 0080	4B
1	4B, 4C	0x0020 0000	2F	0x0000 0400	5B
3	5A, 5B, 5C, 5D, 5G	0x0010 0000	3A	0x0000 0100	5G
1	6B, 6C	0x0004 0000	3F	0x0000 0040	6B
0	7A, 7B, 7C, 7D, 7E, 7F	0x0000 0400	5A	0x0000 0010	7B
		0x0000 0010	7A		
		x00000 0004	7F		
		0x0034 4414		0x0000 05D0	
		COM3		COM4	
		0x0020 0000	2E	0x0020 0000	2D
		0x0004 0000	3E	0x0004 0000	3D
		0x0000 0080	4C	0x0000 0100	5D
		0x0000 0400	5C	0x0000 0004	7D
		0x0000 0010	7C		
		0x0000 0040	7E		
		0x0000 0040	6C		
		0x0024 04D4		0x0024 0104	

COM1 is connected to 2A and 2F (on digit 2), 3A and 3F (on digit 3), 5A (on digit 50), and 7A and 7F (on digit 7). The bit positions are derived from the schematics connection for the GPIO of the MCU and the segment lines (S1 to S24) of the BTL002.

For COM1 and 2A segment, Pin 3 or signal S4 in the schematics has to be active. S4 is in fact DIO_14 of the CC1310 device, so Bit 14 or 0x0000 4000 is set.

For COM1 and 2F segment, Pin 4 or signal S6 in the schematics has to be active. S6 is in fact DIO_21 of the CC1310 device, so Bit 21 or 0x0020 0000 is set.

The same is done for all other segments that are controlled by COM1, and then the bits are ORed together, resulting into the hex value 0x0034 4414.

Then, the same procedure is followed to complete all values for COM2, COM3, and COM4 lines shown in Table 3.

Now the proper GPIO settings for the segment signals have to be combined with the COM hex values for each subphase (out of eight). As seen in Figure 5 for COM0 and COM1, the relevant COM and SEG signals have to be in the opposite polarity and also have the full voltage swing (0 V versus V_{LCD}) to make the segment visible.

Thus, for each subphase due where the COM voltage is either 0 V or V_{LCD}, the SEG signal must have the opposite voltage level. The eight subphases are handled in a switch {} statement; The following is the example code project for the first and second subphases for the COM and segment GPIOs.

The first subphase for all COM lines and segment lines to display the "CC1310" string is the "case 0":

```
…
switch(LCD_stat)  {
    case 0:                             // 1st phase P1
      LCD_stat = 2;                     // go to next state
       PIN_setPortOutputValue(lcdCOMPinHandle, lcdCOMState0);

       PIN_setPortOutputValue(lcdSegPinHandle, lcdSegXCOM1ActState0);
       // push Segment Pin output values into port output

       PIN_setPortOutputEnable(lcdSegPinHandle, lcdSegXCOM1NActState0);
       // switch Output buffers on/off according to desired Segment activity
       break;
…

whereas already calculated:

       lcdCOMState0 = 0x03800200;          // COM Port State for phase 0
       lcdSegXCOM1ActState0 = 0x003FFFFE;  // Seg Pins Active state for phase 0
       lcdSegXCOM1NActState0 = 0x00000000; // Seg OutputEnable state for phase 0
```

The second subphase for COM1 is the "case 2" block inside the switch {} statement:

```
…
    case 2:                             // 2nd phase P2
      LCD_stat = 4;               // go to next state
      PIN_setPortOutputValue(lcdCOMPinHandle, lcdCOMState2);
       // push COM + Base_PWM values into port output
       PIN_setPortOutputValue(lcdSegPinHandle, lcdSegXCOM1ActState2);
        // push Segment Pin output values into port output
      PIN_setPortOutputEnable(lcdSegPinHandle, lcdSegXCOM1NActState2);
      // switch Output buffers on/off according to desired Segment activity
      break;
…
whereas already calculated:
       lcdCOMState2 = 0x04400000;          // COM Port State for phase 2
       lcdSegXCOM1ActState2 = 0x00000000;  // Seg Pins Active state for phase 2
       lcdSegXCOM1NActState2 = 0x00000000; // Seg OutputEnable state for phase 2
```

The other six subphases follow the same procedure—see the heartBeatFxn(UArg arg0, UArg arg1) in "rfPacketTx.c" for the exact values. The parameter LCDFrameCntr is used to adapt the LCD refresh rate.

3.5.3 Porting the GPIO Software Solution to Other 4-MUX, 1/3 Bias LCDs

Obviously, not every application will have the BTL002 display, so porting the code to a customer display is necessary. Before doing this, consider the following:

- The LCD specification (similar to Figure 4) will drive the assignment of COM and SEG lines.
- A detailed map of the COM and SEG lines based on the application schematic has to be created (as shown in Figure 4 and explained for the segment lines).
- The eight subphases for the COMy and BASE_PWMx can be copied "as is", as their waveform is fixed.
- The segment lines for each eight subphases have to be adjusted, based on the characters, that must be displayed on the LCD.
- Precise timing for the LCD GPIO waveforms must be guaranteed—otherwise, DC-free operation is not possible and can damage the LCD.

NOTE: The source code example for the TIDA-00848 is based on the TI RTOS operating system and has been developed to show the software GPIO functionality only. No exact timings have been tested and the correctness of the timings used is not implied.

It is the user's responsibility to ensure that the LCD control in his or her application delivers the correct waveform timing and a DC-free voltage for the LCD, even if other tasks are running on the Cortex-M3 main MCU.

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4 Block Diagram

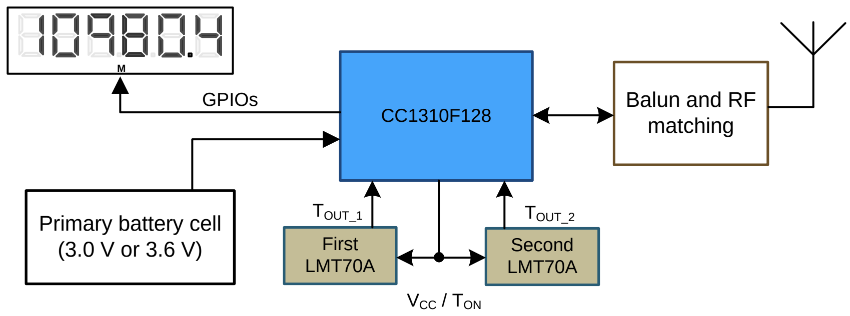

Figure 6. Block Diagram of TIDA-00848

4.1 Highlighted Products

The TIDA-00848 (see Figure 3) has only two main components: the two matched LMT70A temperature sensors and the CC1310 Wireless MCU device with an on-chip sensor controller, RTC module, and 30 GPIO signals.

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

The CC1310 contains an ARM Cortex-M3 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 can 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; thereby significantly reducing power consumption and offloading the main Cortex-M3 CPU.

One of the peripherals in the sensor controller is the SAR ADC module. The ADC is a 12-bit, 200k samples per second 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 connect to up to eight different GPIOs. The peripherals in the sensor controller can also be controlled from the main application processor.

4.1.2 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 LMT70 include virtually any type of temperature sensing where cost effectiveness, high precision, and low power are required, such as IoT sensor nodes, medical thermometers, high-precision instrumentation, and battery-powered devices. The LMT70 is also a great replacement for RTD and precision NTC and PTC thermistors with accuracy specified as:

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

The LMT70A is the matched version of the LMT70 and provides unparalleled temperature matching performance of 0.1°C (max) for two adjacent LMT70A devices picked from the same tape and reel. Dissipating less than 36 μW, the LMT70A has ultralow self-heating supporting its high precision over a wide temperature range. Due to its production precision matching, the LMT70A is an ideal solution for sub-metering applications such as HCAs.

5 Getting Started Hardware

The TIDA-00848 hardware can be programmed and debugged using the J4 connector, which is the 2×5-pin ARM JTAG connector. A 10-pin flat ribbon cable interfaces J4 to a SmartRF06EB board, which includes the XDS100v3 Debugger for programming the CC1310.

When programming the CC1310, disconnecting the jumper J12, which supplies the battery voltage from the battery holder on the back of the PCB, is recommended. J12 can be also used to connect a multimeter device for measuring the approximate average current. Note that due to the very short peaks of the power supply, dedicated equipment such as Agilent N6781A is required for precise current consumption measurements.

To avoid power supply problems between the XDS100v3 Debugger and the battery voltage, use only either of those at the same time or just remove the ½AA battery while debugging the CC1310 code.

5.1 LMT70A Connection to PCB

The TIDA-00848 PCB does not contain the LMT70A sensors because in an HCA application, one temperature sensor should measure the heater body (or heater sensor), and the second sensor should capture the room temperature (or room sensor). Any HCA device is mounted firmly onto the heater body, and the heater temperature sensor should have thermal contact with the heater body. In contrast, the room temperature sensor is orientated into the opposite direction to the room or away from the heater body. The two sensors approach used in this TI Design is described in the DIN EN834 as the "two-sensor measurement method".

Therefore, the required physical placement of these two sensors makes it impractical to solder the LMT70A devices onto the PCB. Instead, this device uses two jumpers (J9 and J11) with the proper signal vias for contacting the two sensors, placed on the small PCB. The LMT70A 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 used. Another I/O pin is saved by using LMT_ON (DIO_28) to enable and power on both LMT70A sensors at the same time.

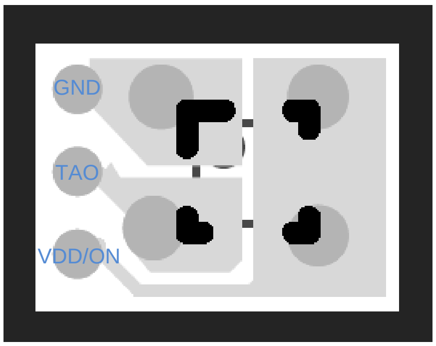

Figure 7. "Small" PCB Layout for LMT70A [5]

Thus, only three pins are required for interfacing to the two LMT70A sensors; each sensor has its own TAO analog output line (LMT1_AIN and LMT2_AIN) connected to an input line of the ADC12. This small PCB (see the application report SNIA021 for full details [5]) has board dimensions of just 2.9 × 2.16 mm. Figure 7 shows the layout of this PCB: the top-left via is GND, the next via is TAO, and the bottom-left via is for both VDD and output enable pins, wired together. The LMT70A is soldered on the back side of the PCB. The required signals for the temperature sensing are:

- DIO_28 = LMT_ON
- DIO_27 = LMT1_AIN (analog input from the first LMT70A sensor)
- DIO_29 = LMT2_AIN (analog input from the second LMT70A sensor)

5.2 Capacitive Touch Area on the PCB

The TIDA-00848 PCB integrates a round area next to the SMA antenna connector for detecting a touch event, based on capacitive sensing approach.

The DIO_30 signal is connected internally to the COMPA module and to this PCB is used to detect the time difference between charging the PCB area (capacitor) without a human finger next to it and with a human finger touching the PCB.

5.3 LCD Connections to CC1310—TI Patent Pending Solution

The CC1310 has in total 30 GPIOs, all accessible to the Cortex-M3 main MCU core. The sensor controller controls 15 of those I/O signals, but only 4 of those are used here, as described in Section 5.1.

All remaining 26 I/O lines are connected to the LCD through a resistor network, as shown in the schematics. The number of required GPIOs with this patent-pending solution is defined by the formula:
(a) GPIOs needed = 4 + 1 for COM0 through COM3 + 1/4 × (required LCD segments)

If INV device is used (main disadvantage is an additional current drawn through the resistor divider 33 kΩ/66.5 kΩ at the INV output).
(b) GPIOs needed = 4 + 2 for COM0-COM3 + 1/4 × (required LCD segments)

If no INV device is used (lower current and no inverter required at the cost of additional GPIO line). To drive 80 LCD segments in the TIDA-00848:

- GPIOs needed = 4 + 1 + 1/4 (80) = 25GPIOs (if a) or 26 GPIOs (if b)

The final solution here is using 26 GPIO lines and the INV on the schematics has been removed.

5.4 Battery Power

The TIDA-00848 has been developed with the goal of supporting both primary cell voltages of 3.0 V (LiMnO2) and 3.6 V (LiSoCl2). These chemistries have significant differences in their behavior, especially under pulse load and ambient temperature. In short, using 3.6-V batteries requires the addition of a buffer capacitor after the battery; here, a Würth device WCAP-ATLI with 1200 µF / 10 V has been selected.

If 3-V batteries from type FDK CR14250SE or the higher capacity FDK CR½6LHT are used [7], then it is possible to completely remove the buffer capacitor of 1200 µF as these batteries can sustain the periodic peak current of 20 mA for 10 ms without lifetime degradation. To properly dimension the buffer capacitor, contact the selected battery manufacturer and provide the current profile of the application as precisely as possible.

6 Getting Started Firmware

A full version of the TI CCS Version: 6.1.2.00015 together with the TI RTOS installation "tirtos_simplelink_2_16_00_08" is required to compile and debug the TIDA-00848 firmware. In addition, Sensor Controller Studio (SCS) 1.2.0.40562—a TI-provided tool chain—is needed to generate the binary code for the sensor controller; SCS can be downloaded at http://www.ti.com/tool/sensor-controller-studio [2]. The firmware code projects for SCS and CCS are provided as a single source code deliverable (TIDA-00848_firmware.zip).

There is one CCS source code project provided, which includes a SCS sub-project, found in the install path /TIDA-00848_RTOS/sce and named "HCA.scp".

6.1 SCS Code Project

To ease developing the program code running on the sensor controller, TI provides a complete tool chain for writing software for the controller, SCS, which is a fully integrated tool consisting of an IDE, compiler, assembler, and linker.

Two tasks have been defined: one for the touch event and the other one for the LMT70A readout.

6.1.1 SCS Task CapTouchButton

The CapTouchButton task uses the COMPA, the TDC, and the ISRC blocks to implement the "touch" event detection.

The PCB area is connected to COMPA input through the DIO_30, while the COMPA reference is the DCOUPL signal, which is nominally at 1.27 V.

The TDC counts the time ticks (in 96-MHz ticks) needed to charge the PCB area (which represents a capacitor between top and bottom layers) to 1.27 V, such that the COMPA changes it output to high.

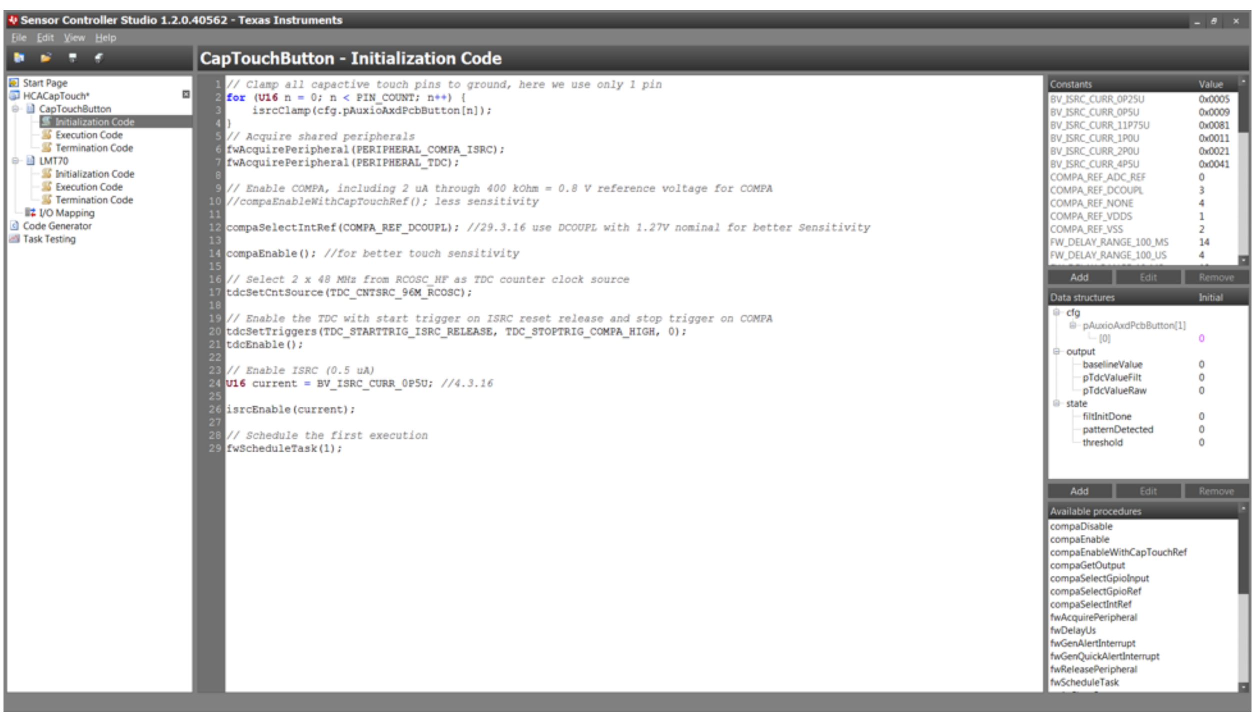

Figure 8. SCS Project for CC1310: CapTouchButton Task (Initialization Code Portion)

The execution code portion for the task is shown in Figure 9:

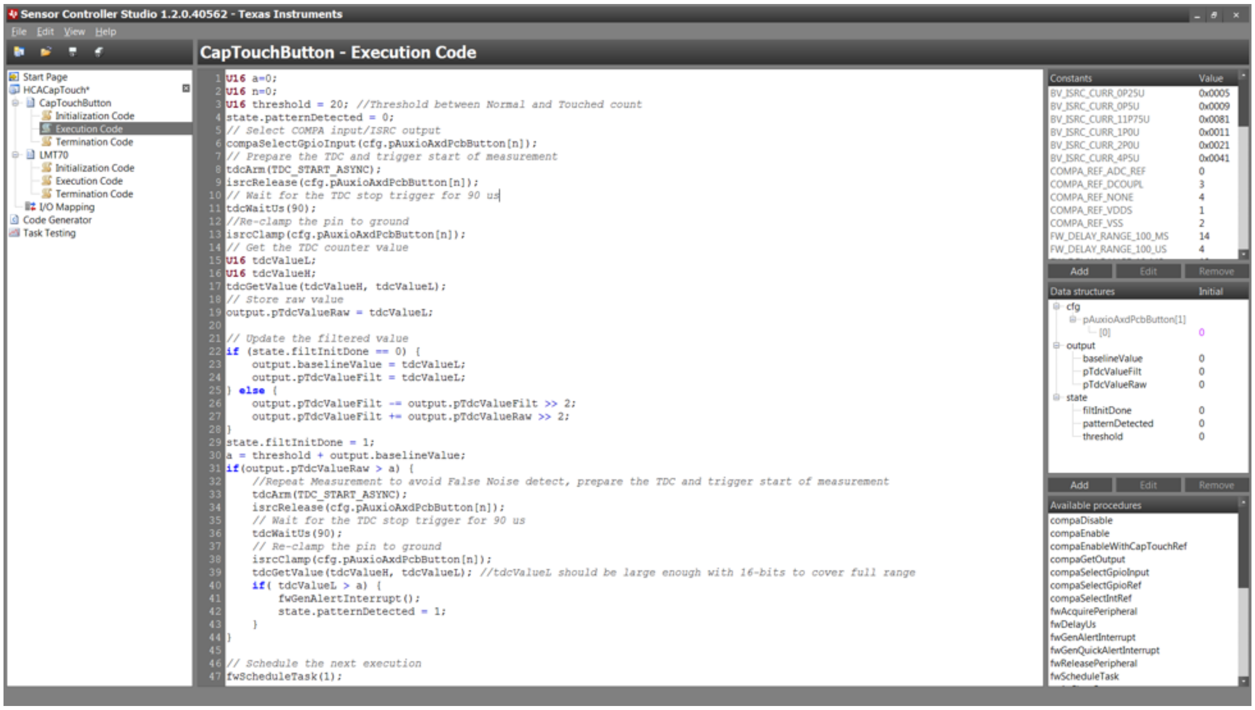

Figure 9. SCS Project for CC1310: CapTouchButton Task (Execution Code Portion)

The variable "threshold" sets the delta between non-touch and touch events (if necessary, the value of 20 can be adjusted). If such delta has been detected, then a second measurement cycle of 90 µs is started to confirm that this is indeed a touch event (and not just an external noise).

If both measurements deliver a delta value above the threshold, then an interrupt to the Cortex-M3 core is raised using the fwGenAlertInterrupt() function. The CapTouchTask is rescheduled to run in one 1 RTOS tick later, where the RTOS tick has been set to 1 second.

6.1.2 SCS Task LMT70

The task LMT70 is defined in the execution code, as shown in Figure 10:

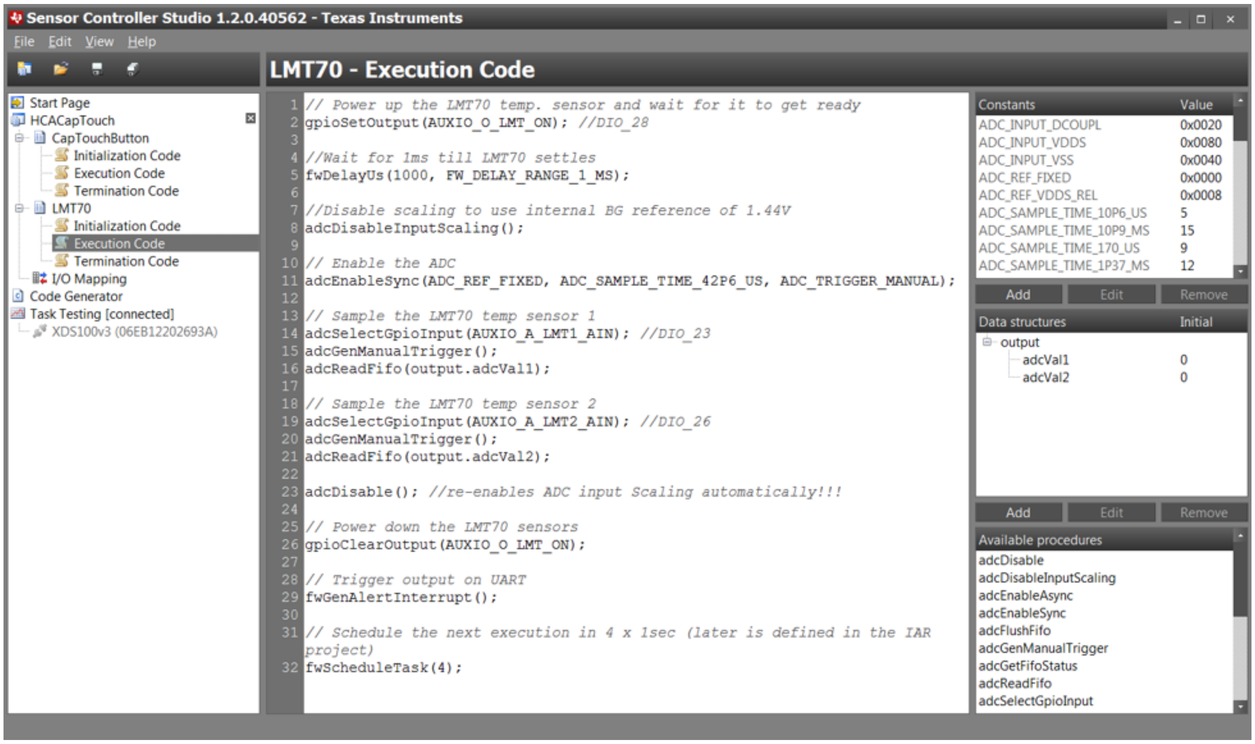

Figure 10. SCS Project for CC1310: LMT70 Task (Execution Code Portion)

The signal LMT_ON is set active, thus both enabling and powering on the two LMT70A sensors. A timeout of 1 ms is required for the output of the LMT70A to settle, so the task waits for that period before disabling the internal ADC scaling. Next, the ADC12 module is enabled and the sampling time is set to 42.6 µs. The two LMT70A sensors are sampled one after the other. The ADC12 is then disabled, and the LMT_ON signal is set to low (inactive) to save power.

The task raises an interrupt to the M3 core and schedules itself to run in four RTOS ticks (here equal to 4 seconds).

6.2 CCS Code Project

The sensor controller code has been integrated inside the /sce folder within the TIDA-00848 firmware. The /wmbus folder contains the functionality to generate valid wM-Bus data packets, for the S-, T-, and C-modes in transmit direction and has been functionally tested. The receive operation of wM-Bus packets has not been considered in the TIDA-00848.

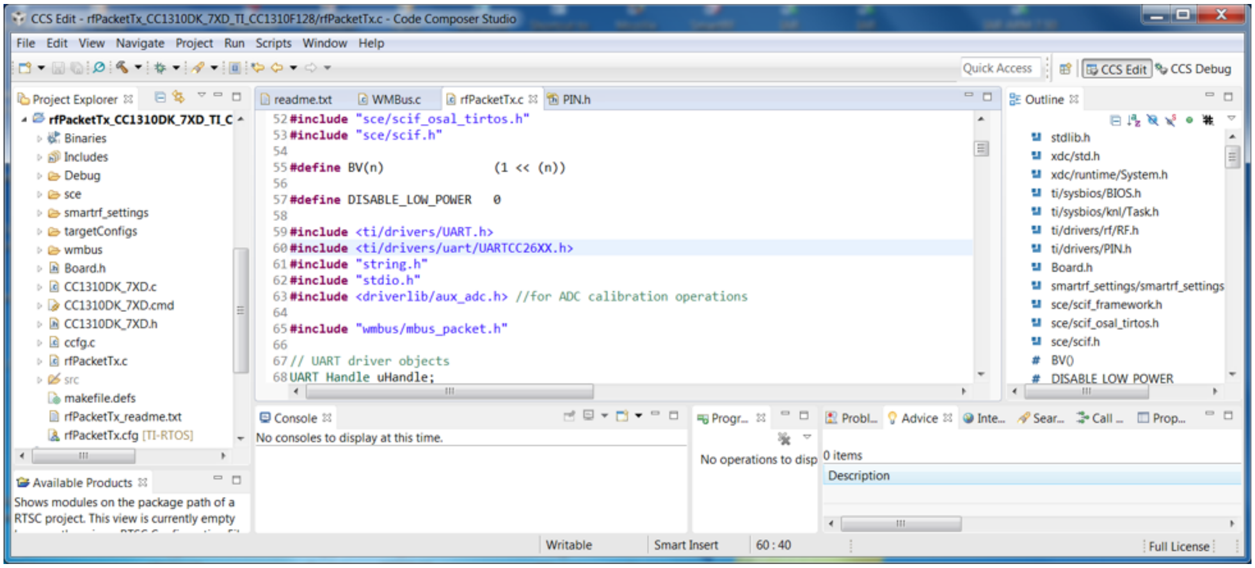

Figure 11. CCS Project for TIDA-00848: Combines wM-Bus TX Example With Sensor Controller Tasks

7 Test Setup

Two different test setups have been used to develop and test the TIDA-00848: one for the wM-Bus at 868-MHz RF functionality and one to evaluate the current consumption.

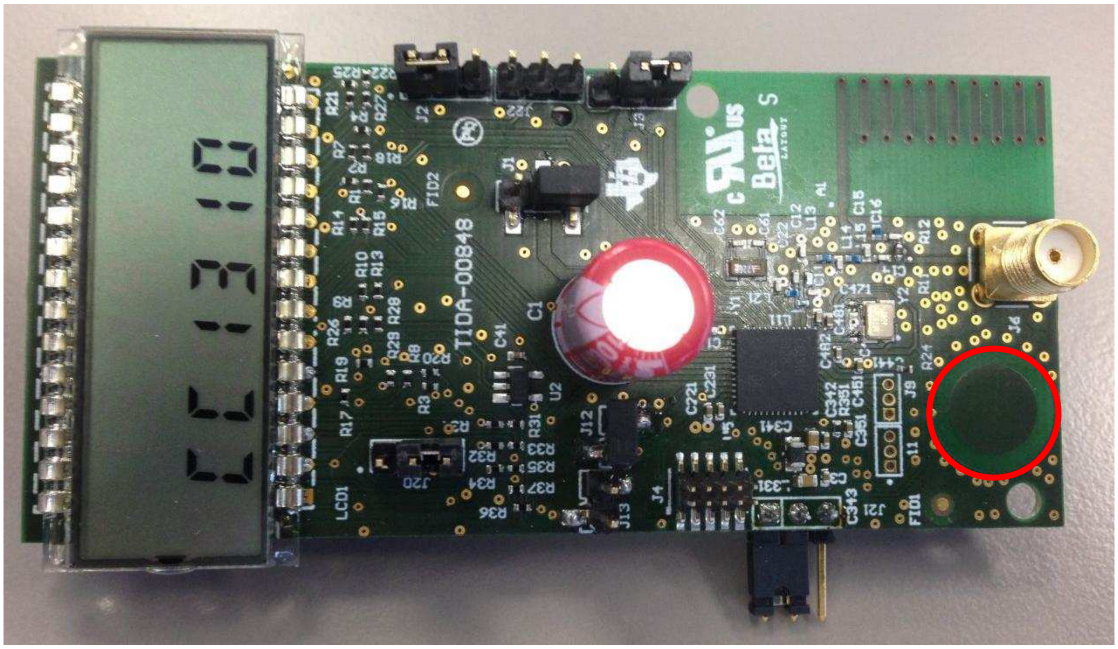

Figure 12. PCB Area for CapTouch (Red Circle) for Implementing LCD On/Off Functionality

The wM-Bus functionality, or the packet data contents of the transmission, has been verified using two different hardware kits as receivers. A Radiocrafts RC1180MBUS Kit [8] with an S- and T-mode Packet Sniffer GUI (included in the RCTools MBUS setup [9]) captured and checked the wM-Bus data packets in S- and T-mode, transmitted by the TIDA-00848.

For testing both T- and C-mode reception, a CC1310EM and SRF06EB board with a dedicated XML configuration file (also included) was used. Note that the XML files for the SmartRF7 Studio tool for proper packet reception of S-, T-, and C-modes are provided in the TIDA-00848 firmware package named tidcc91.zip (TIDCC91).

8 Test Data

The TIDA-00848 hardware is tested in several steps, focusing on three areas:

- LCD with sufficient contrast on all 80 segments
- Sensor controller tasks (CapTouch event detection)
- RF transmissions

8.1 Sensor Controller Task for CapTouch Detection

The "pattern detected" variable at the bottom graph is representing the touch event; the output.pTdcValueRaw and output.pTdcValueFilt show the number of 96-MHz ticks measured (Raw) and after some simple filtering (Filt).

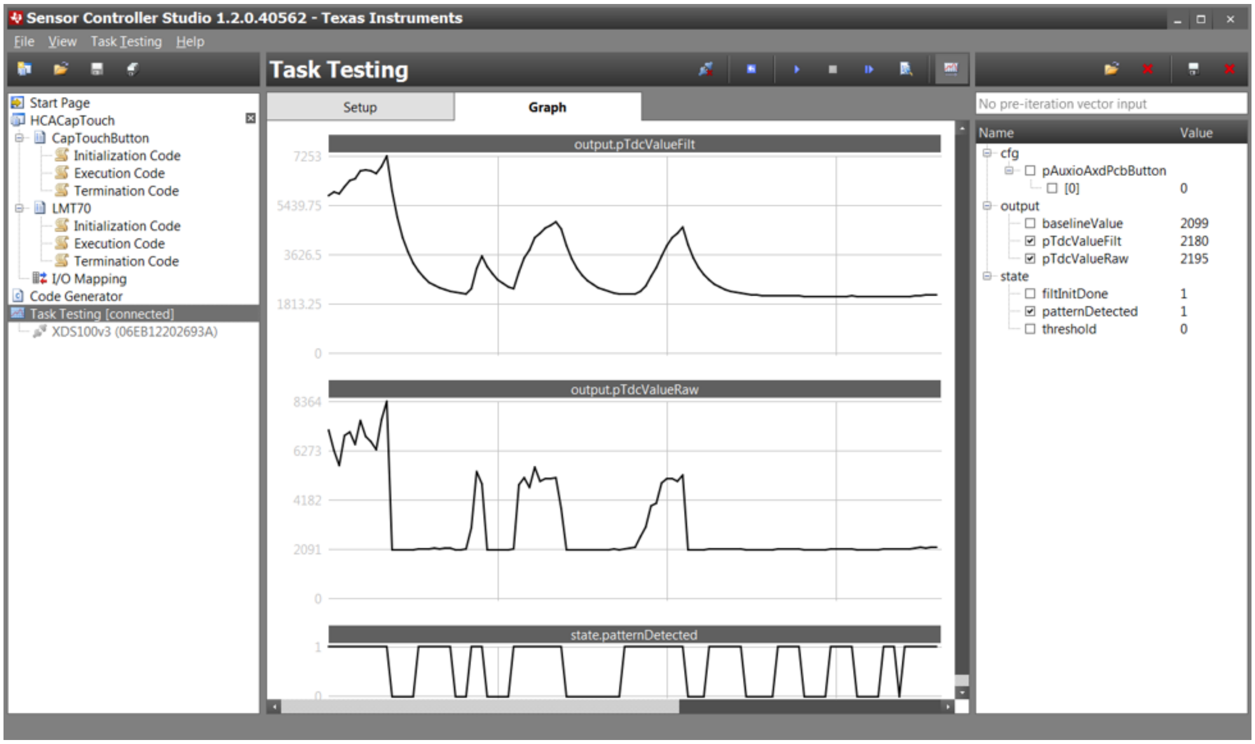

Figure 13. Task Testing Under SCS: Touch Events are the Peaks in the Two Upper Graphs

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NOTE: The second task LMT70 has been reused from the TIDA-00636 and no further testing has been done.

8.2 wM-Bus Transmission Packets in S-, T-, and C-Modes

Proper transmit operation of the TIDA-00848 has been documented in the screenshot in Figure 14. The HEX content of the data is based on the example data packet of EN13757-4, here modified with the Texas Instruments vendor identifier of "51 33" (displayed in LSB first format).

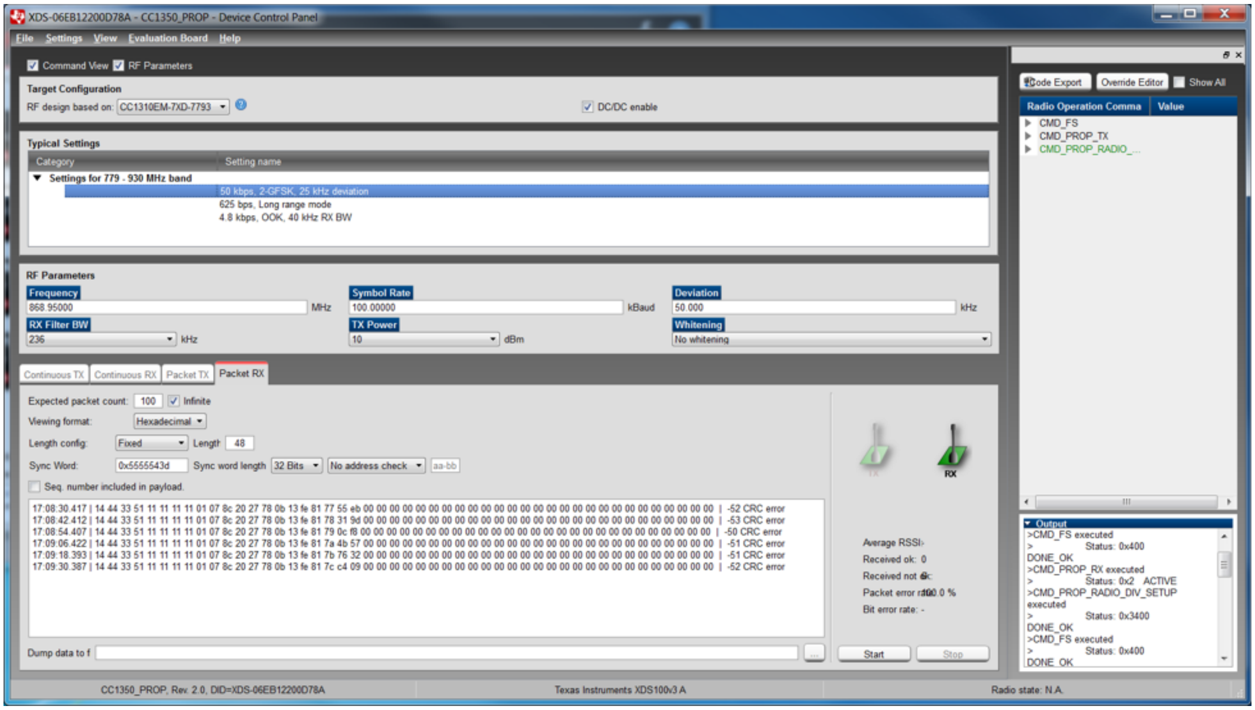

Figure 14. C-Mode Telegrams Received With CC1310DK Using "T-Mode" SRF7 Studio XML File

8.3 LCD

Two different values for the inverted BASE_PWM_N line and the serial resistors for the segment lines have been tested. The serial resistors R1 through R4, R7 through R10, R13 through R17, R19 through R22, R5 through R27, with 3 MΩ and 10 MΩ have been tested; the latter value delivered lower average current while the LCD contrast did not change or deteriorate visibly.

Also the R28 with 11 kΩ and R29 with 22 kΩ initially, have been increased to 33.2 kΩ and 66.5 kΩ to better fit the 10-MΩ serial resistors.

8.4 TIDA-00848 Current Consumption

The power consumption of the TIDA-00848 was measured with an Agilent N6781A two-quadrant source or measure unit for battery drain analysis. Figure 15 shows an 835-nA average current at a 3.6-V supply voltage when the sensor controller is running periodically the CapTouchTask only and LCD functionality is off. There is a period of 8 seconds between LCD activities, and this is indicated by the two markers in Figure 15.

For comparison, the same activity (LCD off) was measured using a 3-V supply and showed a 1.064-µA average current. When the LCD is enabled, current consumption is significantly higher, as shown in Figure 16. The value is 337.79 µA at 3.6 V, due to the periodic (approximately 1 ms) wake-up of the Cortex-M3 MCU through the TI RTOS. After each wake-up, all eight subphases of the f_{frame} are executed.

During this LCD on/off testing, no RF task was enabled—just a minimalistic firmware IAR project has been used.

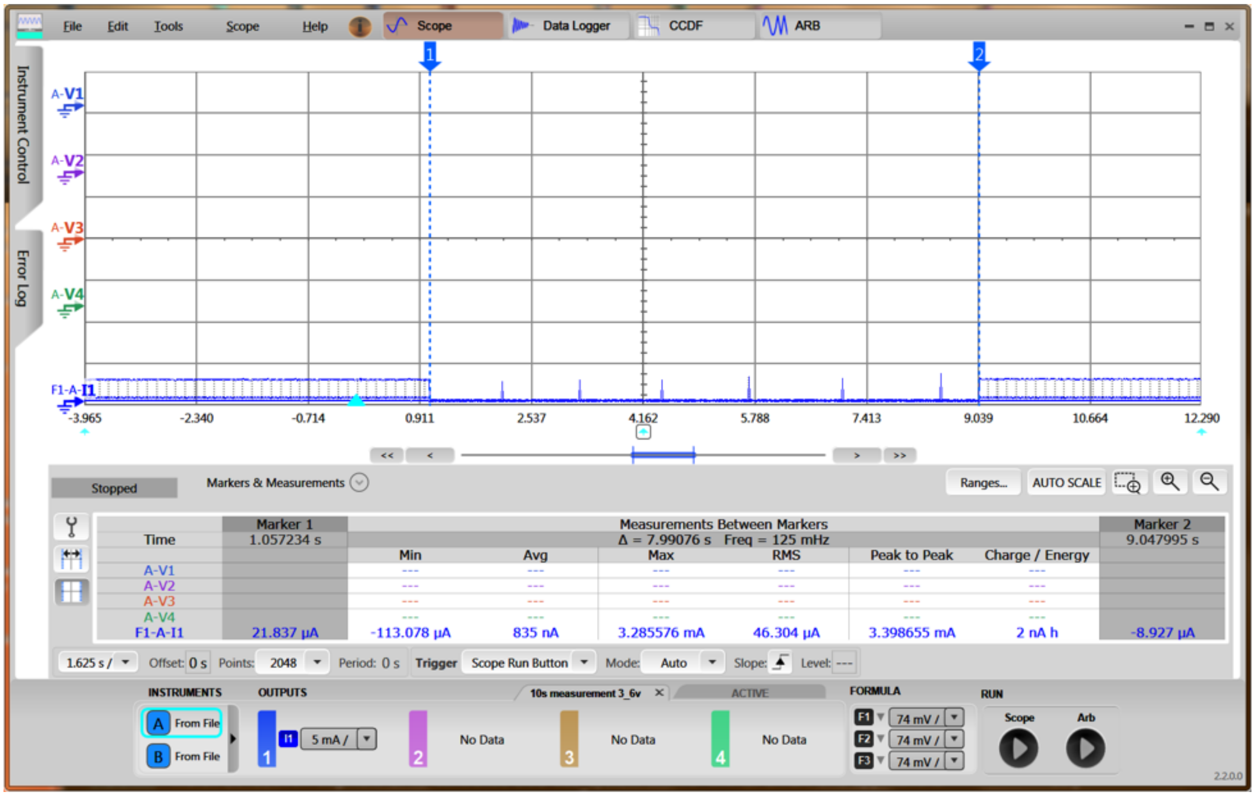

Figure 15. Current Average at 3.6 V (LCD is Off, Sensor Controller With CapTouch Task Only)

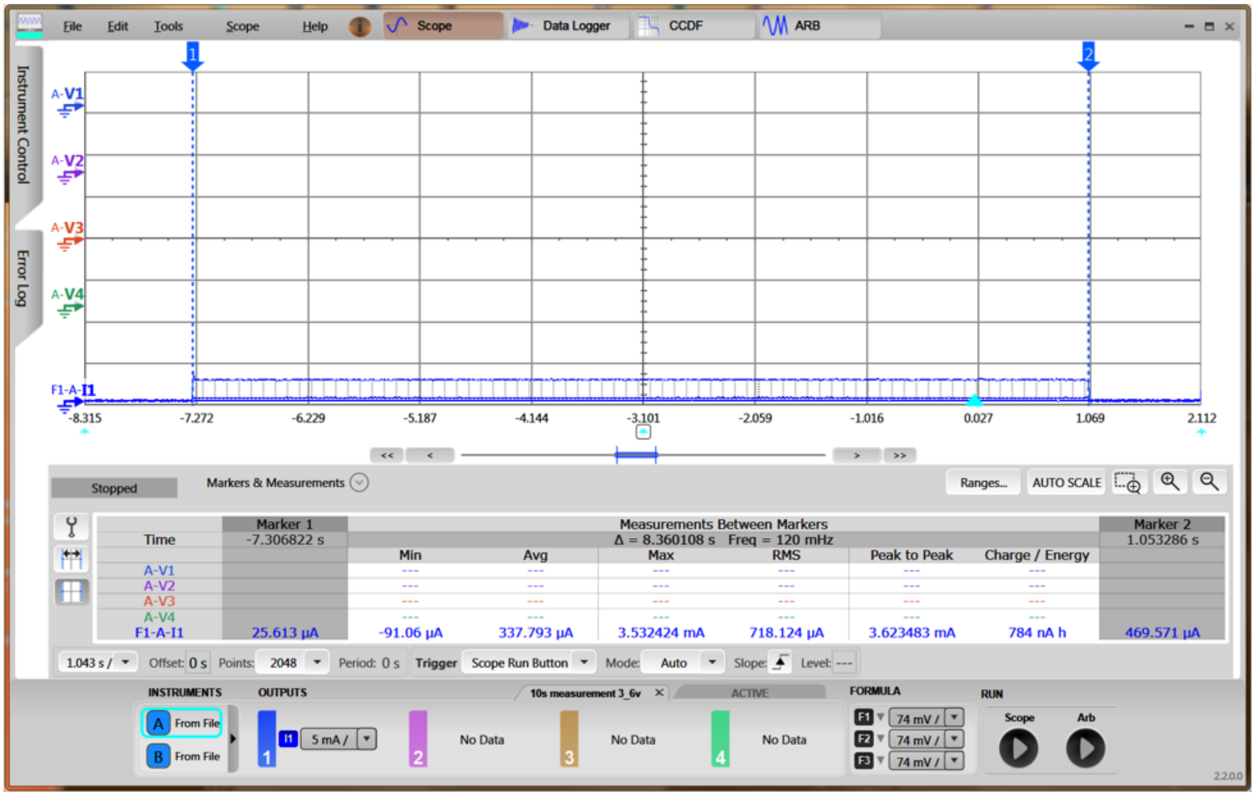

Figure 16. Current Average at 3.6 V (LCD is On, Sensor Controller With CapTouch Task Only)

9 Design Files

9.1 Schematics

To download the schematics, see the design files at TIDA-00848.

9.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00848.

9.3 PCB Layout Recommendations

The TIDA-00848 is a two-layer PCB with approximately 1-mm overall thickness; the two layers are for the lowest cost while the 1-mm thickness increases the mechanical stability of the PCB. The layout closely follows the CC1310 reference design in [4] but has been modified on the top layer copper to achieve 50-Ω strip-line impedance of the RF line to the SMA antenna connector.

9.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-00848.

9.4 Altium Project

To download the Altium project files, see the design files at TIDA-00848.

9.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00848.

9.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00848.

10 Software Files

To download the software files, see the design files at TIDA-00848.

11 References

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12 Terminology

Heat cost allocators (HCAs)—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)

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

wM-Bus— The European RF metering standard, providing solutions for the 169-, 433-, and 868-MHz bands

LCD— Liquid crystal display

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 the Chemnitz University of Technology (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 has focused on metering and sub-1GHz 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 Smart Home & Metering summits in Munich.

The author would like to give special recognition to **PETER SPEVAK**, TI MGTS member and group technical staff, for contributing his *SW controlled Segment-LCD using GPIOs* patent-pending idea and his involvement in the hardware and software design effort for the TIDA-00848.

Revision A History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (June 2016) to A Revision	Page
• Changed from preview page	1

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