Design Guide: TIDA-01624

Bluetooth®-Enabled, High-Accuracy Skin Temperature Measurement Flex PCB Patch Reference Design

TEXAS INSTRUMENTS

Description

This reference design demonstrates highly-accurate sensing of skin temperature using the TMP117 high-precision digital temperature sensor with the CC2640R2F wireless MCU. This users guide provides design guidance for skin temperature measurement in medical and wearable applications along with an evaluation software and smart device application.

Resources

TIDA-01624	Design Folder
TMP117	Product Folder
CC2640R2F	Product Folder

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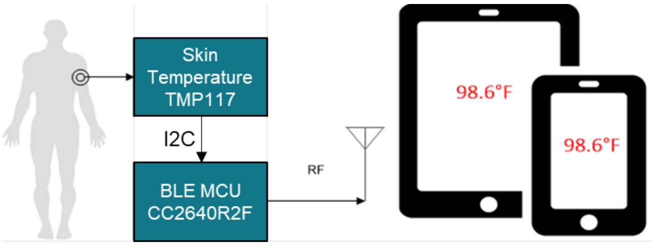
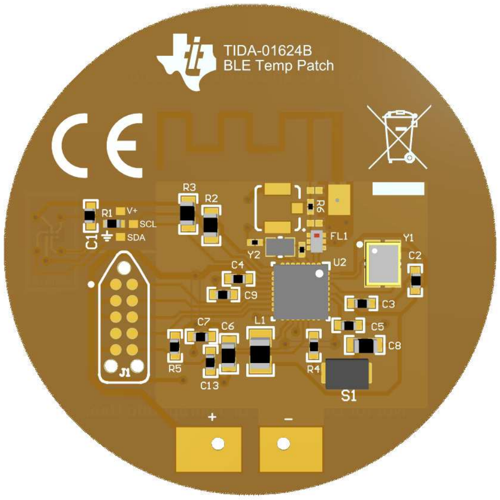
Features

- High accuracy (±0.1ºC) temperature measurement around human body temperature
- 2.4-GHz RF transceiver compatible with Bluetooth® low energy (BLE) 4.2 and 5 specifications
- Integrated PCB antenna
- Flexible PCB design
- Up to 3 years of shelf life along with 5 days of active time
- iOS app for device monitoring

Applications

- Medical devices
- Healthcare
- Wearables





1 System Description

With the need to integrate sensors into newer wireless and cloud applications, the Bluetooth-enabled, high-accuracy skin temperature measurement flex patch provides a wireless solution for receiving high accuracy skin temperature measurements on a Bluetooth-capable device, such as a smart phone or tablet.

Through direct contact with the skin, the TMP117 high-accuracy, low-power, digital temperature sensor can send 16-bit digital output data through the I²C to a CC2640R2F SimpleLink™ Bluetooth low energy (BLE) wireless microcontroller (MCU). After collecting this data, the CC2640R2F can use Bluetooth protocol to transmit the data to a Bluetooth-connected device.

The patch is designed to operate with a 3-V, flexible thin-film battery, requiring very low power consumption of the design components. For testing and demonstration purposes, the designer can use the large contact pads of the device to receive external power from other sources when a battery is not connected.

There are two primary modes of operation for the patch: active and inactive mode. When the patch is inactive, the CC2640R2F enters a complete shutdown state and the TMP117 is powered down. This mode allows a multiple year shelf life for the patch without a significant depletion of stored energy in the battery. When the designer presses the wake-up switch, the flex patch enters active mode and the TMP117 begins reading and auto-advertising temperature data the CC2640R2F BLE device can receive.

When the designer uses the software as designed, the only way to return the patch from active mode back to inactive mode is to remove and reapply the device power. In healthcare applications, reuse or extended use of monitoring patches may pose risks to patient health due to hygiene concerns. The software for this patch was created with the intent to make the design disposable so that each patch can only be used once. An alternative for temperature-monitoring systems is to use a removable covering that can be disposed of after use. This is common in designs of probe-type thermometers for oral temperature measurements. If this method is used, the system and these covers must be characterized as the final design. For probes, the designer can modify the software to move between active and inactive mode, but an MCU must be in the probe to use Bluetooth communication protocol under this modification.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Operating power supply range	+1.8 VDC to +3.8 VDC	Limited by CC2640R2 and TMP117 supply range
Operating temperature	–40ºC to +85ºC	Limited by operating range of CC2640R2
Temperature accuracy	±0.1ºC (max) from +35ºC to +43ºC	Exceed requirements for human body temperature measurements
RF range	>10 meters	BLE 4.2/5
Form factor	2-layer flexible PCB	

2 System Overview

2.1 Block Diagram

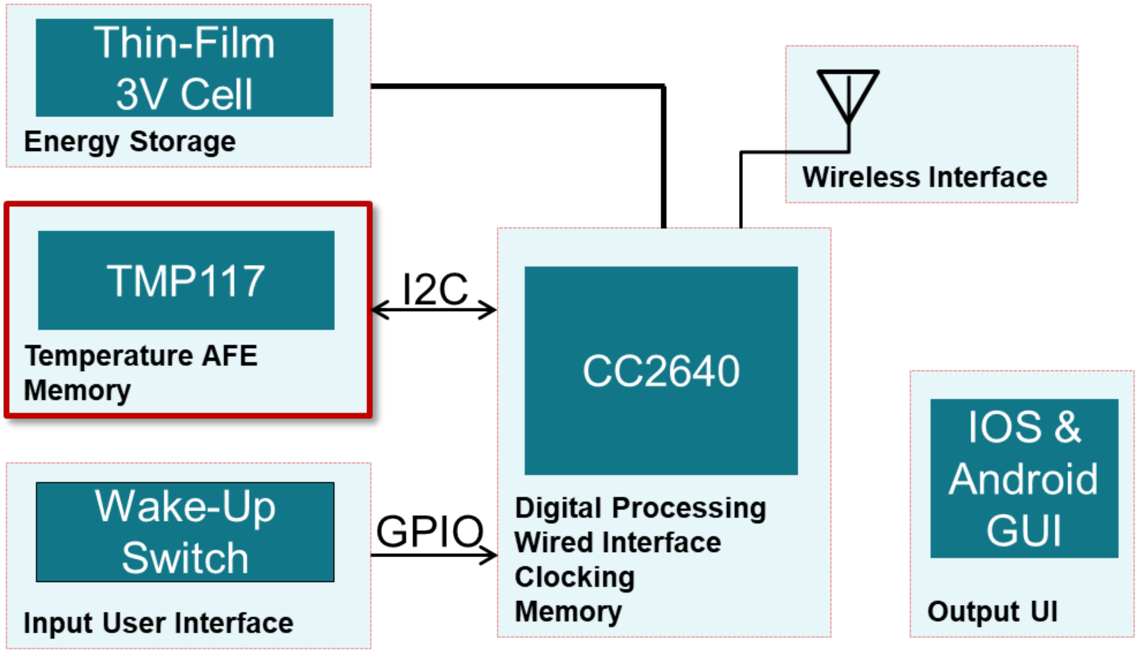


Figure 1. TIDA-01624 Block Diagram

2.2 Design Considerations

Carefully consider the placement of the patch to ensure that the temperature reading is aligned with the expected results. The average temperature reading of an oral thermometer in a healthy adult is 98.6ºF (37ºC) , but measurements taken from other areas of the body will differ in temperature. For example, a temporal thermometer will read a temperature that can be up to one degree (1ºF) lower than that of an oral thermometer.

The crucial distinction here is between *core temperature* and *skin temperature.* The primary goal of this design is to demonstrate effective techniques for the measurement of skin temperature. The temperature at the surface of a patient's skin will not normally be identical to their core temperature. The most accurate methods of obtaining core temperature are internal, such as with oral or rectal thermometers. In certain applications however, such as long-term patient monitoring in the incubator of a NICU, skin temperature monitoring is often the only practical method. Skin temperature can also be used in conjunction with other parameters in applications such as fitness trackers and heart-rate monitors.

When using skin temperature to try and obtain a measurement close to core temperature, the preferred sites are traditionally the underarm (axillary) or the forehead (temporal). The form factor of this patch demonstrates a generic circular form that can be used anywhere on the skin. For axillary measurements, it may be desirable to extend the TMP117 away from the primary portion of the board to allow the RF antenna to be exposed on one side while the sensor is enclosed underneath the user's arm.

The effective Bluetooth range of the design will depend on many factors, such as walls and objects between the patch and the smart device. When worn, however, the primary source of signal loss will likely be the patch wearer. To improve the range, the CC2640R2F can be programed to increase its Bluetooth output power, but this will decrease the battery life of the patch. Under normal operation, the patch is powered by a thin-film cell, therefore low power Bluetooth modes are recommended for this design to extend operating time. As characterized this design uses the maximum output power of the CC2640R2F to attain a longer range. Alternatively, antenna and pi-network matching may be performed while the device is worn to increase the signal range without increasing the output power level of the CC2640R2F.

2.3 Highlighted Products

The Bluetooth-Enabled High Accuracy Skin Temperature Measurement Flex PCB Patch features the following devices:

- TMP117 – High-accuracy, low-power, digital temperature sensor
- CC2640R2F – SimpleLink™ Bluetooth® low energy wireless MCU

2.3.1 TMP117 Description

The TMP117 is a low-power, high-precision temperature sensor that provides a 16-bit temperature result, with a resolution of 7.8125 m°C and an accuracy of up to ±0.1°C with no calibration. The TMP117 operates from 1.8 V to 5.5 V, consuming 3.5 µA typically, and comes in both a 2.00 × 2.00 mm WSON package, and a 1.53 x 1.00 mm WCSP package. The device also features integrated EEPROM, and a temperature offset register which can contain single-point calibration data.

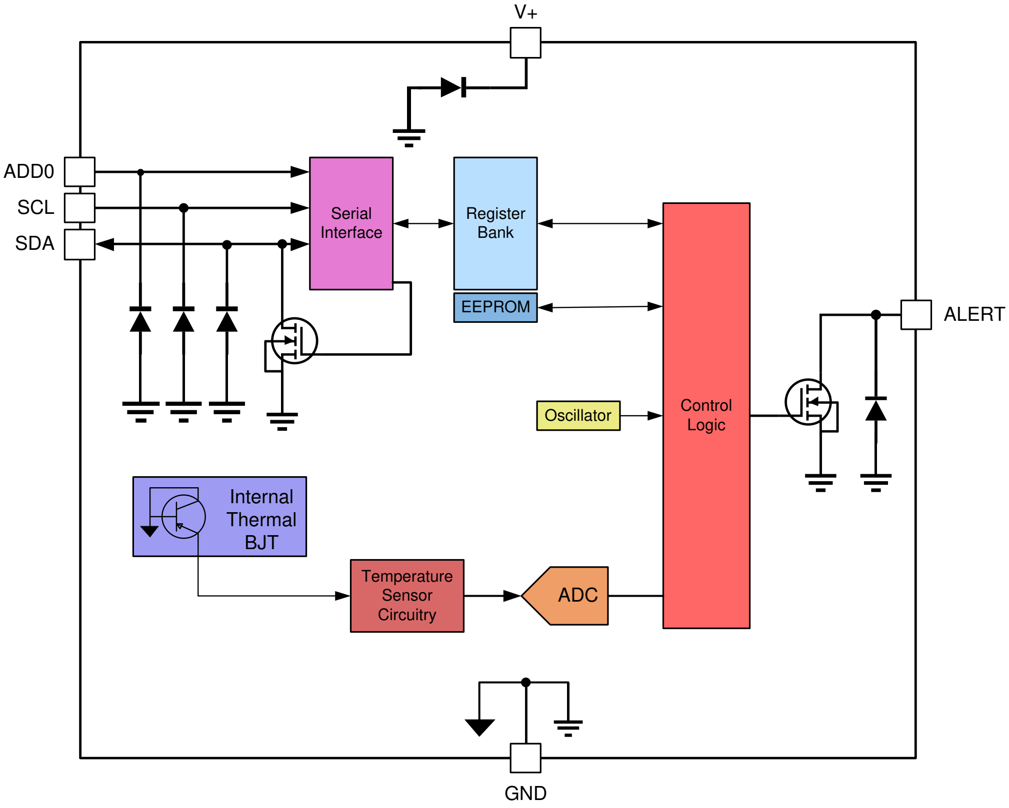


Figure 2. TMP117 Internal Block Diagram

2.3.2 CC2640R2F Description

The SimpleLink, Bluetooth low energy CC2640R2F is a wireless microcontroller (MCU) targeting Bluetooth 4.2 and Bluetooth 5 low energy applications. The low active RF and MCU currents and low-power mode current consumption can provide excellent lifetime for energy-harvesting applications or applications that require small batteries.

The CC2640R2F device contains a 32-bit Arm® Cortex®-M3 core that runs at 48 MHz as the main processor. The device also has a rich peripheral feature set that includes a unique ultra-low power sensor controller.

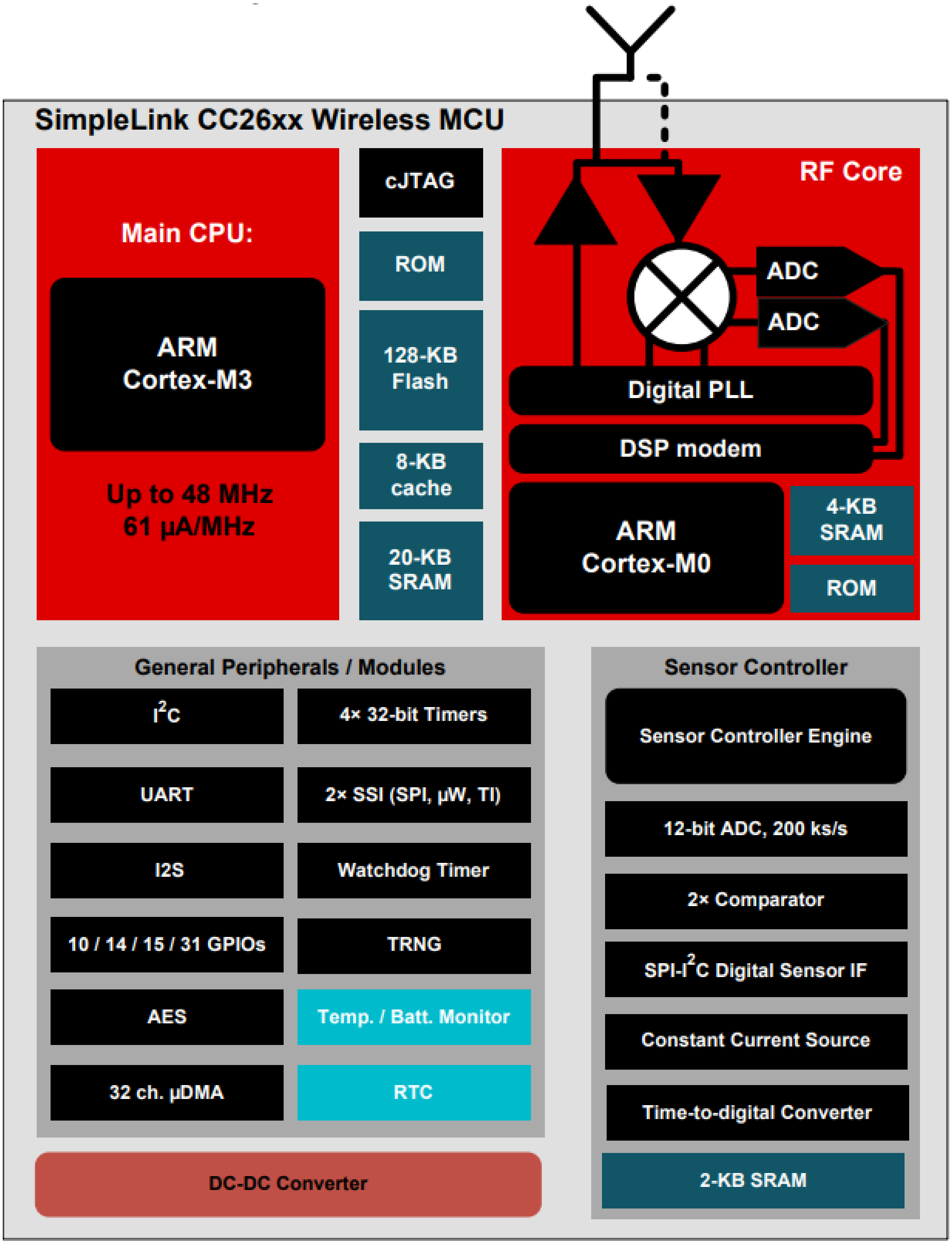


Figure 3. CC640R2F Block Diagram

2.4 System Design Theory

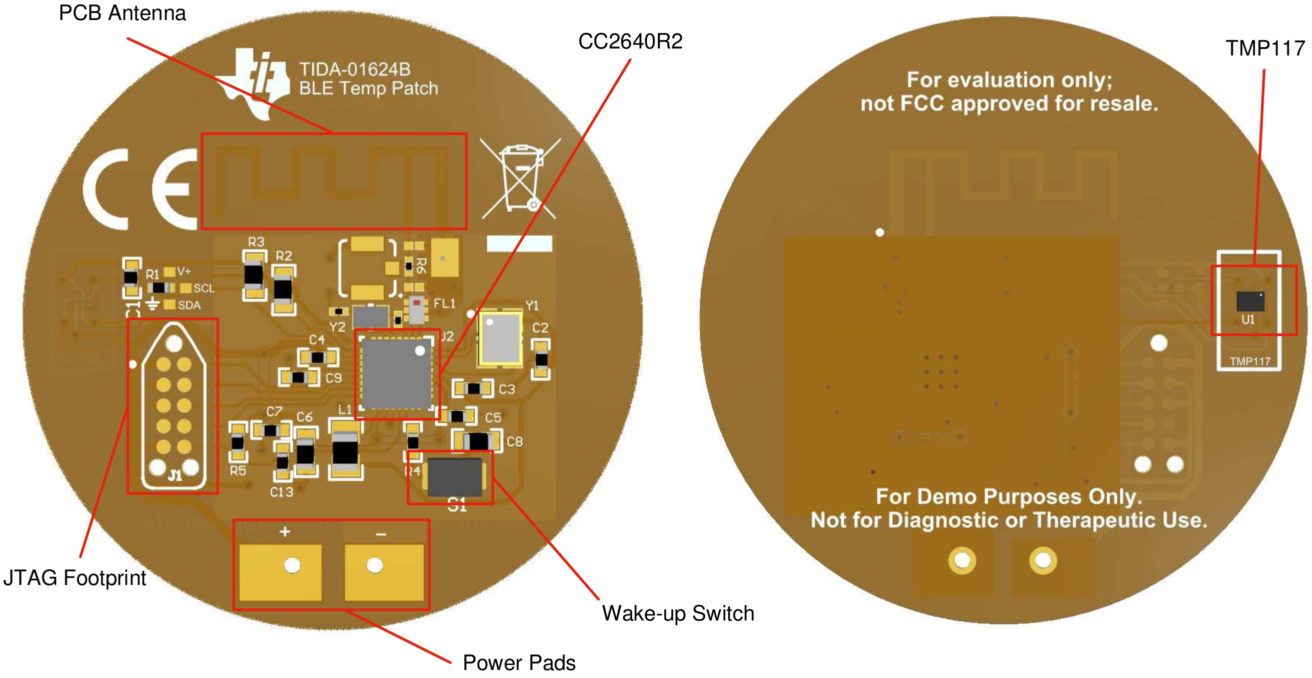


Figure 4. Key Features in Design Layout

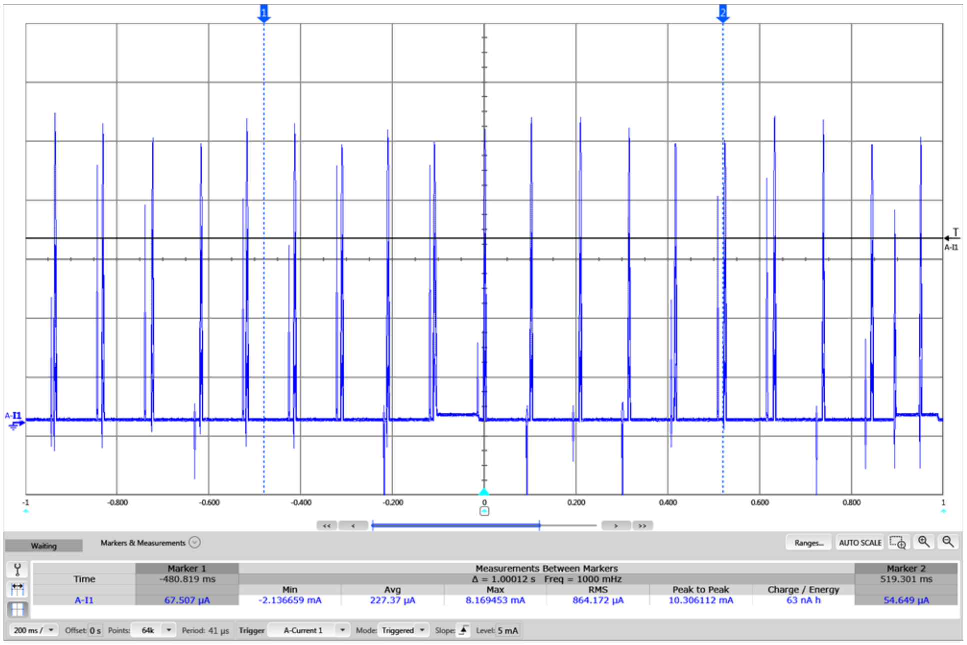
The system design requirements for wearable patches can vary in certain applications. The requirements considered for this design include:

- Shelf Life
- Active Life
- Range
- Wearer Comfort
- System Accuracy

2.4.1 Shelf Life and Active Life

The power budget for this design is based on the shelf life (inactive state) and active life (active state) requirements for the design. In the Bluetooth-enabled high-accuracy skin temperature flex patch, the CC2640R2F is configured in shutdown mode until the tactile switch (S1) is pressed and triggers the patch to wake up. Due to the overall low current consumption for the TMP117, the temperature sensor is powered using one of the CC2640R2 GPIOs. This reduces the total design shutdown current by removing the temperature sensor's shutdown current from consideration. Thus, the current consumption of the design in shutdown mode is now limited to 150 nA, which is primarily from the CC2640R2 MCU. As a result, the overall shelf life for this design is expected to be 3 years. This life span is limited by the typical shelf life of the battery itself and not by the charge storage. If using an alternate power source, shelf-life may change accordingly.

For active life time requirements, temperature patches may be expected to operate for up to a few days after the patches are attached to a wearer. Current consumption can be reduced by limiting the frequency of measurement, and by transmitting temperature data alongside the auto-advertisement pulse. Section 3.2.2.1 shows the current consumption results for the Bluetooth-enabled high-accuracy skin temperature flex patch. If the patch is active but not connected to the wearer, the patch will auto-advertise up to 10 times a second, measure temperature at 1-second intervals, and have an expected run time greater than 5 days. When connected, the active life time is expected to be around 3 and a half days.



	Marker 1	Measurements Between Markers						Marker 2
Time	-480.819 ms	Δ = 1.00012 s Freq = 1000 mHz						519.301 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	67.507 µA	-2.136659 mA	227.37 µA	8.169453 mA	864.172 µA	10.306112 mA	63 nA h	54.649 µA

200 ms / Offset: 0 s Points: 64k Period: 41 µs Trigger A-Current 1 Mode: Triggered Slope: Level: 5 mA

Figure 5. Power Meter Capture of Current Draw During 10-Hz Auto-Advertisement

2.4.2 Range

Range on the BLE broadcast is highly dependent on both the initial output power from the antenna and layout of the board. To minimize the human body attenuation of the signal, the RF antenna should be exposed on one side to allow for better signal propagation and range. While worn, the device output power from the on-board F-type antenna is roughly –48 dBm at close range without any matching performed. This gives the patch an expected range of greater than 12m (39 feet). This is dependent on the sensitivity of the receiver and any obstacles that may be in the device path. Section 3.2.2.2 shows the testing used to determine the range of the design. In practice, a range of roughly 40 feet in an open environment was observed.

2.4.3 Wearer Comfort

This design used a 2-layer flex PCB to reduce thermal mass and maximize board flexibility. The primary benefit of flexibility is the ease and comfort for the wearers, which improves the likelihood that the patch will remain static on the patient. Regions such as the RF portion that require solid ground planes should be kept as small as possible to minimize the portion of the board that feels rigid to the wearer. Wearer comfort can not be quantified, so it important to consider this factor in the design of any final products. It may be desirable to enclose a final system in soft-gauze or various types of bandages to pad between the board and the wearer. If this is done, take care to ensure that the thermal path between the TMP117 and the wearer's skin is still optimized for response time and accuracy. The final product must also be characterized with the expected packaging included. The recommendations listed in the *Layout considerations for wearable temperature sensing* (SNOAA03) and *Design challenges of wireless patient temperature monitors* (SNOAA07) application reports may help the designer improve system response time and accuracy.

2.4.4 System Accuracy

For compliance under the ISO-80601 and ASTM E1112 medical standards for intermittent patient temperature monitors, system accuracy must be verified using a liquid bath and a highly accurate reference. Table 2 shows a summary of these accuracy requirements as specified by ASTM E1112. The TMP117 is designed to exceed these requirements, but the designer must also consider the temperature offset caused by the integration of the device into a design for total system accuracy. A single-point calibration around the center of the desired range can ensure accuracy within most systems, and this offset correction can be stored within the temperature offset register of the TMP117. The design accuracy for the BLE flex patch was tested in a sample set inside a liquid oil bath and was within the requirements listed in Table 2 without the need for any offset correction.

If an offset is necessary in production systems, the designer must test a statistically significant sample of the final product to determine the ideal offset for the TMP117, or plan to perform a calibration during manufacturing.

Table 2. Temperature Accuracy Requirements Under ASTM E1112

TEMPERATURE (ºC)	MAXIMUM ERROR (ºC)
< 35.8	± 0.3
35.8 - 37	± 0.2
37.0 - 39.0	± 0.1
39.0 - 41.0	± 0.2
> 41.0	± 0.3

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

Unless otherwise noted, the design was implemented and tested with the following battery specifications:

- Voltage: 3.0 V
- Min Capacity: 35 mAh
- Max Cont. Discharge Rate: 17.5 mA

3.1.1 Hardware

A computer and JTAG programmer are required to program the device. A smart phone or tablet (iOS) are required to communicate with the device when it is in use.

3.1.2 Software

The design has an embedded firmware that must be programmed to the patch. To compile and load the embedded firmware, the following software is required:

- Code Composer Studio version 8.2 or above
- SimpleLink™ CC2640R2 SDK – Bluetooth® low energy
- SmartRF Flash Programmer v2 (optional)

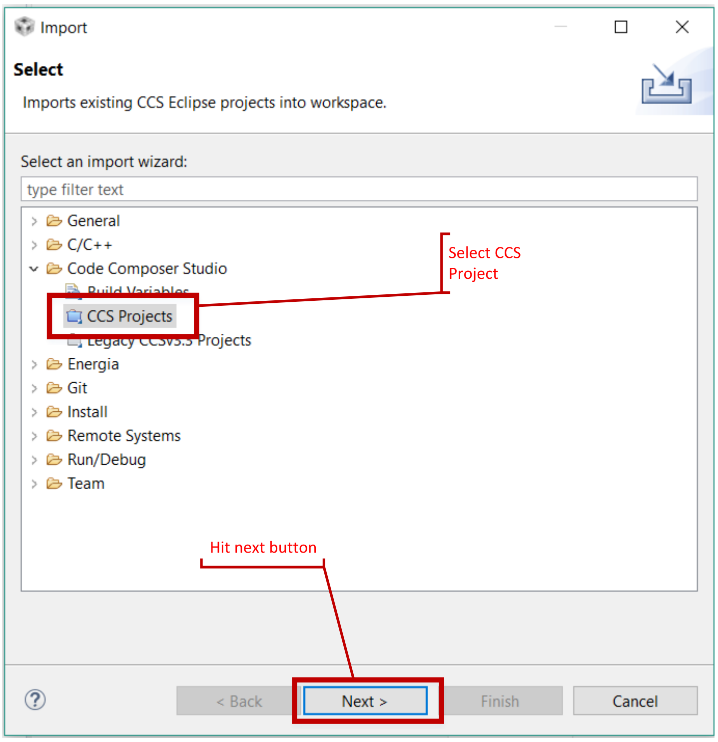
To view the temperature from the patch or connect to the patch, the following application is required on an iOS-enabled smart phone or tablet.

- SimpleLink™ SDK Explorer

3.1.2.1 Building Embedded Firmware

The first step is to compile the design's embedded firmware. Assuming that the CCSv8.2 and SimpleLink SDK for the CC2640R2 is installed, the user must follow these steps:

1. Download the zip file for the firmware and extract it locally on your PC
2. Copy the folder "tida_01624" from the extracted zip package and copy it to the SimpleLink CC2640R2 SDK installation path "C:\ti\simplelink_cc2640r2_sdk_2_20_00_49\examples\rtos\CC2640R2_LAUNCHXL\blestack"
3. Start CCSv8.2 and import the project by clicking on File → Import. This will launch the import dialog box. Expand Code Composer Studio → CCS Projects. Click on Next button as shown in Figure 6.



Imports existing CCS Eclipse projects into workspace.

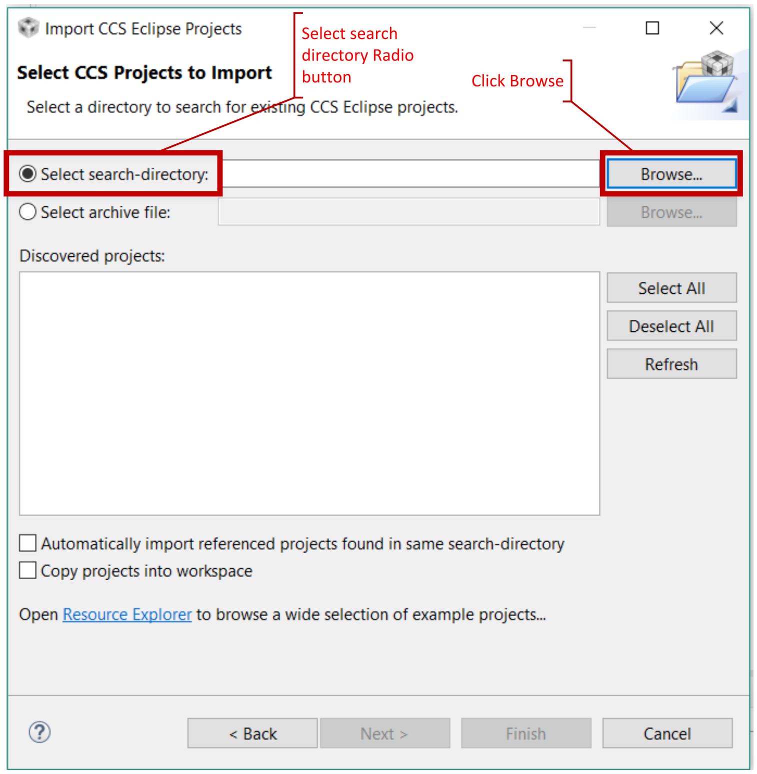
Select an import wizard:

Select CCS Project

Hit next button

Figure 6. Software Import Menu

4. Select the "Select search-directory" radio button in the pop-up window and click on the browse button as shown in Figure 7.



Select a directory to search for existing CCS Eclipse projects.

● Select search-directory:

○ Select archive file:

Discovered projects:

☐ Automatically import referenced projects found in same search-directory

☐ Copy projects into workspace

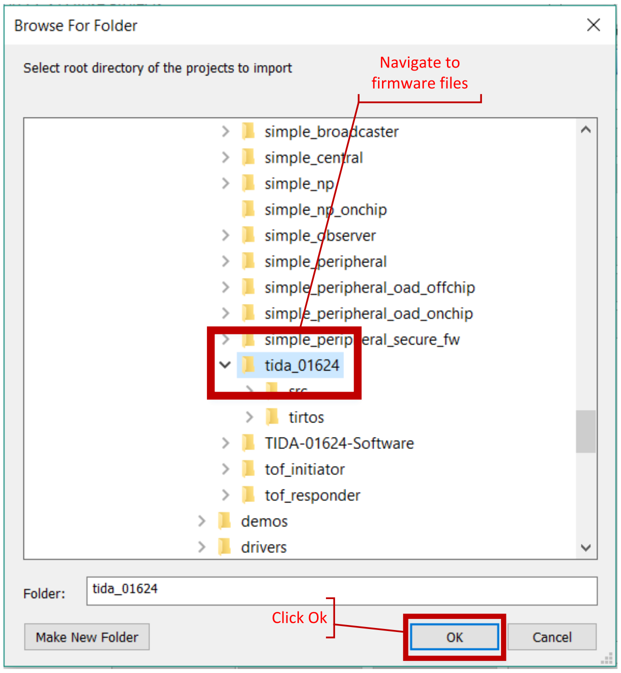
Open Resource Explorer to browse a wide selection of example projects...

Select search directory Radio button

Click Browse

Figure 7. Import Project Menu

5. Navigate to the path where the firmware project is placed in the SimpleLink CC2640R2 SDK and then click OK as shown in Figure 8.



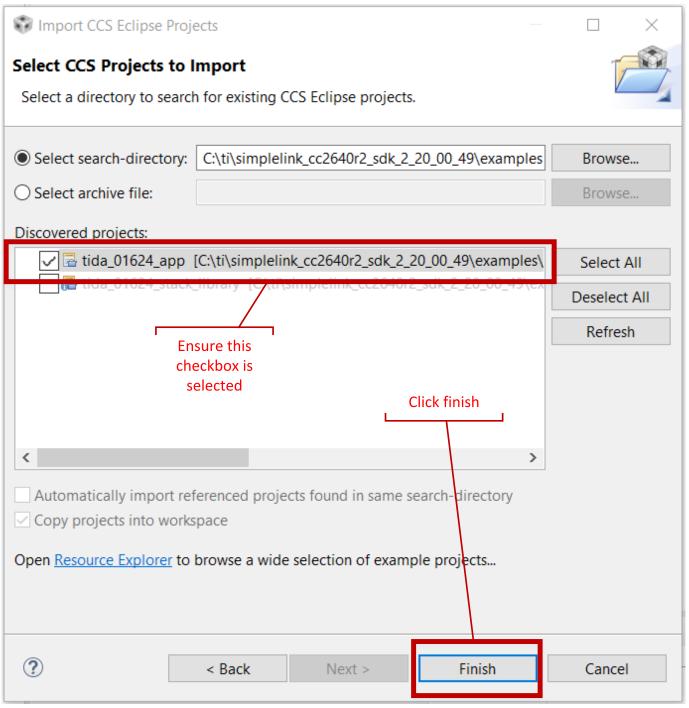
Navigate to firmware files

Folder: tida_01624

Click Ok

Figure 8. Project Browser

6. Ensure that the checkbox for tida_01624_app is selected as shown in Figure 9, then click finish. This will import the CCS project.



● Select search-directory: C:\ti\simplelink_cc2640r2_sdk_2_20_00_49\examples

○ Select archive file:

Discovered projects:

☑ tida_01624_app [C:\ti\simplelink_cc2640r2_sdk_2_20_00_49\examples\

☐ tida_01624_stack_library

☐ Automatically import referenced projects found in same search-directory

☑ Copy projects into workspace

Ensure this checkbox is selected

Click finish

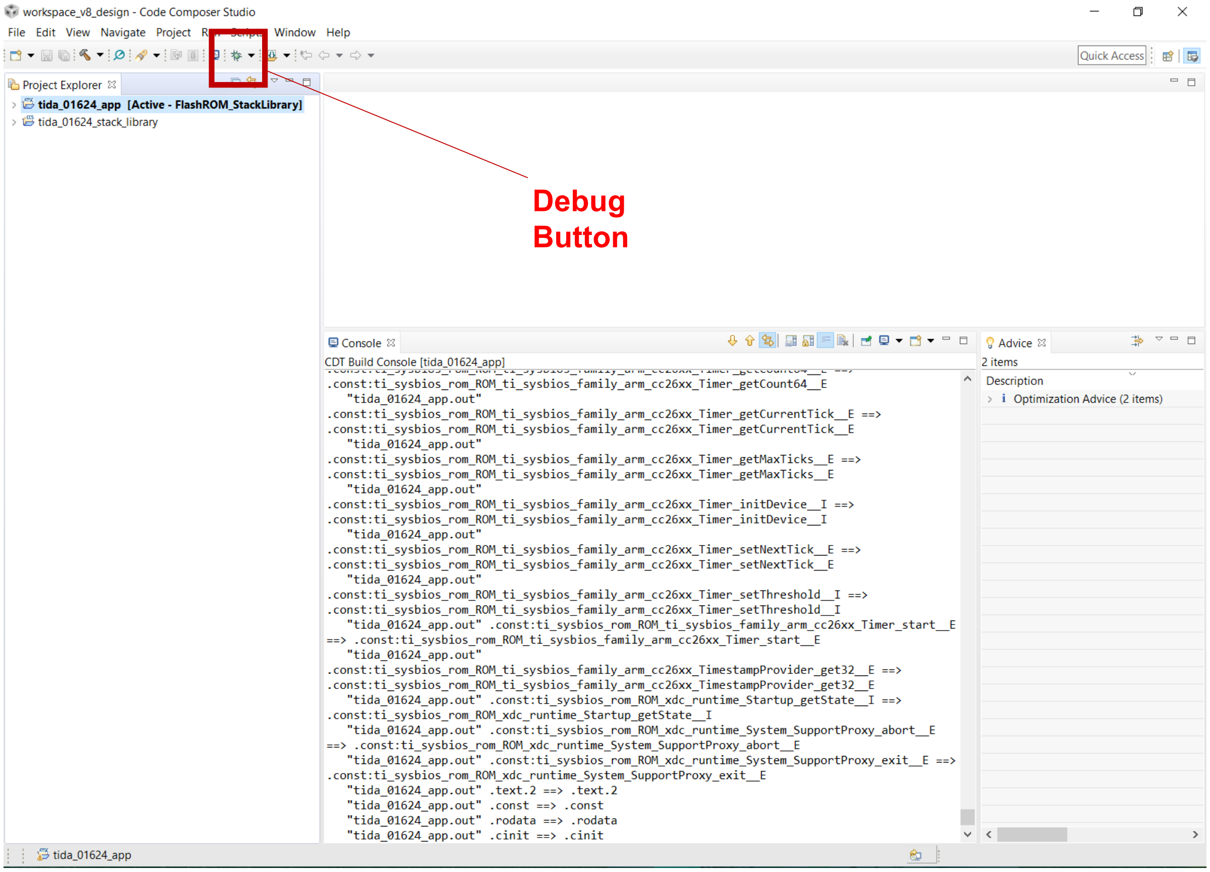
Figure 9. CCS Project Importing

7. In the Project explorer, right-click on tida_01624_app and click on Build Project in the drop-down menu. It may take up to a minute for the compilation to complete. Once the build is successful, the programming output file is generated.

3.1.2.2 Downloading the Embedded Firmware

To download the firmware to the board, an XDS110 USB Debug Probe is required. The XDS110 USB Debug probe can come as a standalone programmer or from most TI LaunchPad™ development kits. For this design, we configured a TI LaunchPad to work as an XDS110 USB Debug probe along with a 10-pin ribbon cable compatible with the 10-pin Tag-Connect™ footprint.

After configuring the LaunchPad, the designer can click on the Debug button shown in to download the firmware using CCSv8.2 (see Figure 10).



```
.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_getCount64__E
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.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_getCurrentTick__E ==>
.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_getCurrentTick__E
   "tida_01624_app.out"
.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_getMaxTicks__E ==>
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.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_initDevice__I ==>
.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_initDevice__I
   "tida_01624_app.out"
.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_setNextTick__E ==>
.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_setNextTick__E
   "tida_01624_app.out"
.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_setThreshold__I ==>
.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_setThreshold__I
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==> .const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_Timer_start__E
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.const:ti_sysbios_rom_ROM_ti_sysbios_family_arm_cc26xx_TimestampProvider_get32__E
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.const:ti_sysbios_rom_ROM_xdc_runtime_Startup_getState__I
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.const:ti_sysbios_rom_ROM_xdc_runtime_System_SupportProxy_exit__E
   "tida_01624_app.out" .text.2 ==> .text.2
   "tida_01624_app.out" .const ==> .const
   "tida_01624_app.out" .rodata ==> .rodata
   "tida_01624_app.out" .cinit ==> .cinit
```

Figure 10. Downloading Firmware to the CC2640R2.

3.1.2.3 Reading From the Patch

This section lists the steps on how to read the patch and navigate through the SimpleLink SDK Explorer App. Reading from a patch requires a nearby smartphone and a power-source for the device. Figure 11 to Figure 14 show how to navigate the SimpleLink SDK Explorer app.

1. On start-up, Simplelink SDK Explorer will default to the standard SDK BLE Plugin (see Figure 11). You can change this by selecting the SDK BLE Plugin under "Current Product".

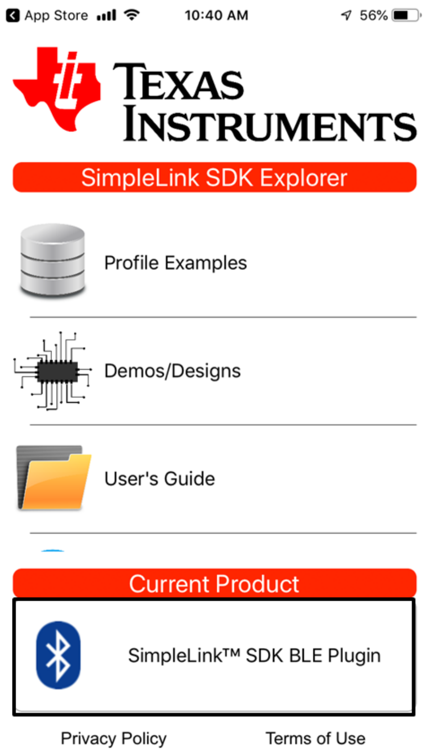
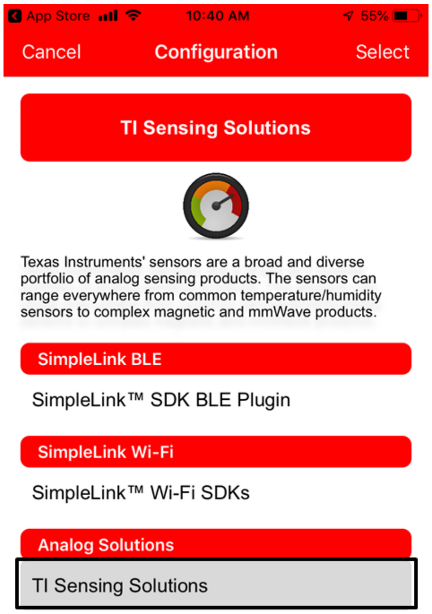


Figure 11. SimpleLink SDK Explorer Main Page

2. Select **TI Sensing Solutions** below the list of products



Texas Instruments' sensors are a broad and diverse portfolio of analog sensing products. The sensors can range everywhere from common temperature/humidity sensors to complex magnetic and mmWave products.

Figure 12. TI Sensing Solutions

3. Return to the home page and select **Demos/Designs**

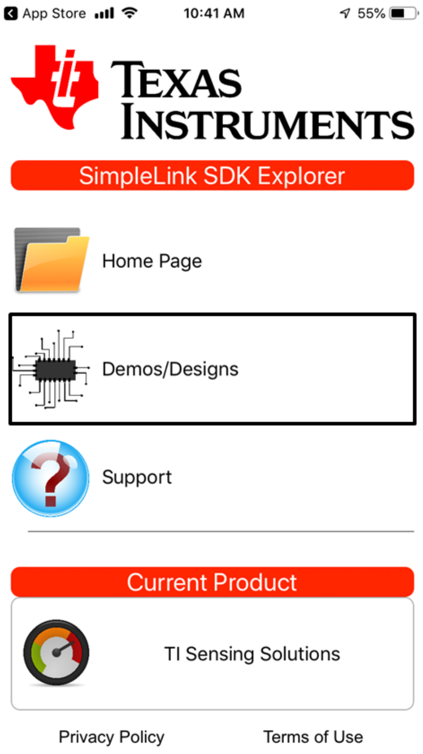


Figure 13. Home Page With the TI Sensing Solutions Product Selected

4. Select **Temperature Sensor Medical Patch** below Demos/Designs to find the TMP117 BLE Flex Patch.

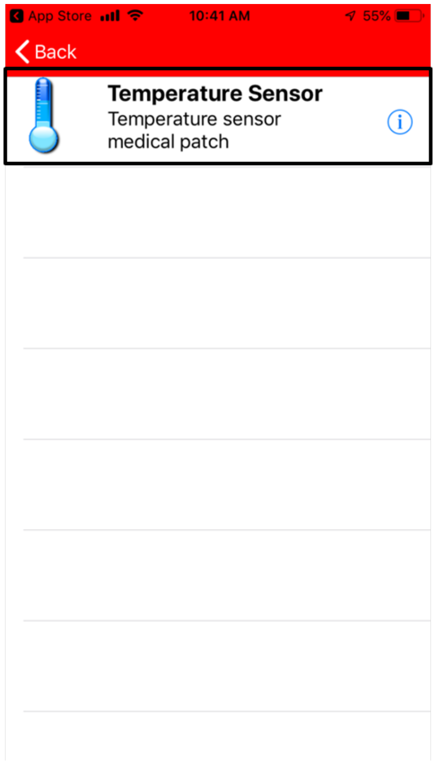


Figure 14. Temperature Sensor Medical Patch Demo. Select to Search for Patches in the Area.

3.2 Testing and Results

3.2.1 Test Setup

3.2.1.1 Current Consumption and Life Span

For initial current consumption tests, the power pads on the wireless patch were connected to a power analyzer capable of measuring currents in the nA range. The average current numbers collected were used to estimate the expected life span of the device under battery power. For practical testing of life span, the patch was enabled and left running in auto-advertisement mode. Temperature data was still available more than 4 days from initial start-up of the patch when running on a 35mAh battery.

3.2.1.2 Range

Traditionally a measurement of effective isotropic radiated power (EIRP) would be a good tool to estimate the total range of an RF system, but with a wearable medical patch, there will be significant absorption of the RF signal from the human body. Therefore, the best method for verifying the range of the patch was determined to be demonstration. The output power of the patch while worn was measured using a Bluetooth explorer app from a smart phone, and the range of the patch in open air can be calculated based on an assumed receiver quality. To verify this, one of the patches was worn for an extended period, adhered to the engineer using an FDA-approved TegaDerm ™ patch. The range of the device was periodically tested using the detection of regular temperature updates from the auto-advertisement pulses as indication, and was used to confirm the initial calculations.

3.2.1.3 System Accuracy

ASTM E1112 recommends testing of system accuracy using a liquid bath with a calibrated probe of at least 30m°C accuracy. The test setup used for verifying the design temperature accuracy is intended to mimic this setup. During accuracy testing, one of the patches is submerged in a liquid oil bath and powered through an external 3-V supply. The bath is then moved through various points in the human body temperature range, and multiple readings are taken to correlate with the calibrated probe.

3.2.2 Test Results

Sections Section 3.2.2.1 through Section 3.2.2.3 explain the results of the testing performed on the patch.

3.2.2.1 Current Consumption/Life-Span

Figure 15 to Figure 20 show the current consumption of the patch under various settings. In the final design, the patch was configured to auto-advertise every 100 ms, and read temperature every 1 second. This places the average current consumption around roughly 230 µA, which means that the active life time of the patch was greater than 5 days after initialization on the 35 mAh battery. This greatly exceeds the 12-24 hour specifications for most wireless monitoring temperature patches available today. The design run time was confirmed by expending one of the flexible cells entirely after enabling the patch. Equation 1 shows how to estimate the patch lifetime depending on the total connection period.

$$T_{ACTIVE} = Q_{Batt}/(X(I_{Connected}) + (1-X)I_{Auto})$$

where

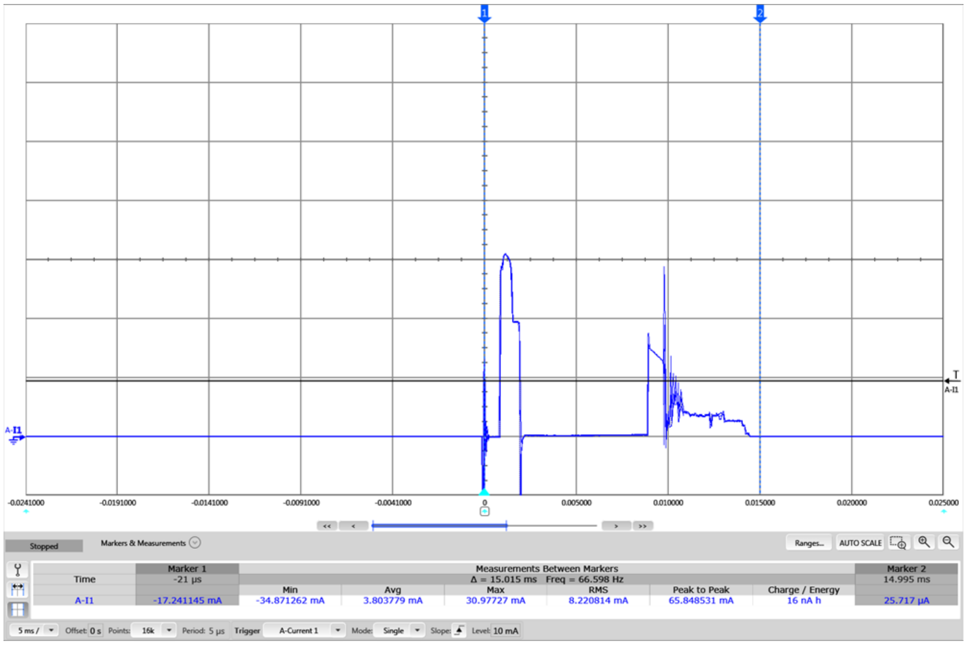
- T_{Active} is the runtime of the patch (in hours)
- Q_{Batt} is the charge stored in the battery (in mAh)
- X is the percentage of time the patch is expected to be connected to a smart device.
- $I_{Connected}$ and I_{Active} are the average current consumption (in mA) of the design when connected to a smart device, and when auto-advertising. (1)

Table 3. Average Current Consumption

CONDITION	MEASURED CURRENT DRAW	ASSOCIATED FIGURE	EXPECTED RUNTIME
Initial Startup	3.8 mA (Avg) for 21 µs	Figure 15	N/A

Table 3. Average Current Consumption (continued)

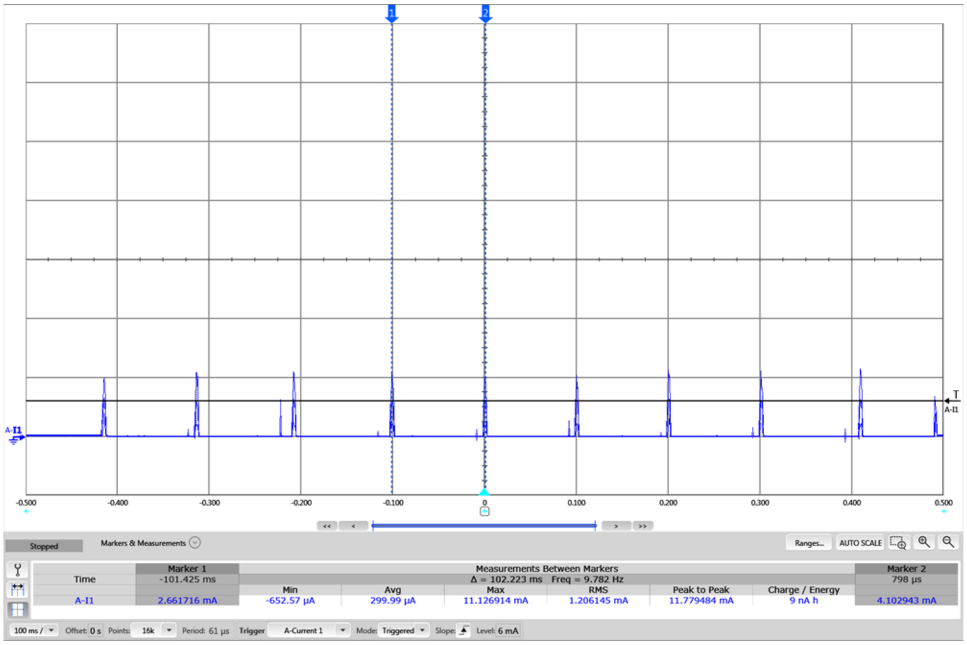
CONDITION	MEASURED CURRENT DRAW	ASSOCIATED FIGURE	EXPECTED RUNTIME
During Auto-Advertisement	11.1 mA (Peak)	Figure 16	N/A
100 ms (10 Hz) Auto-Advertisement	227.37 µA (Avg)	Figure 17	153.93 hours, or 6.4 days
1 Sec (1 Hz) Auto-Advertisement	106.204 µA (Avg)	Figure 18	329.6 hours, or 13.7 days
Connected to Smart Device	420.743 µA (Avg)	Figure 20	83.2 Hours, or 3.5 days



	Marker 1	Measurements Between Markers						Marker 2
Time	-21 µs	Δ = 15.015 ms Freq = 66.598 Hz						14.995 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	-17.241145 mA	-34.871262 mA	3.803779 mA	30.97727 mA	8.220814 mA	65.848531 mA	16 nA h	25.717 µA

5 ms / Offset: 0 s Points: 16k Period: 5 µs Trigger A-Current 1 Mode: Single Slope: Level: 10 mA

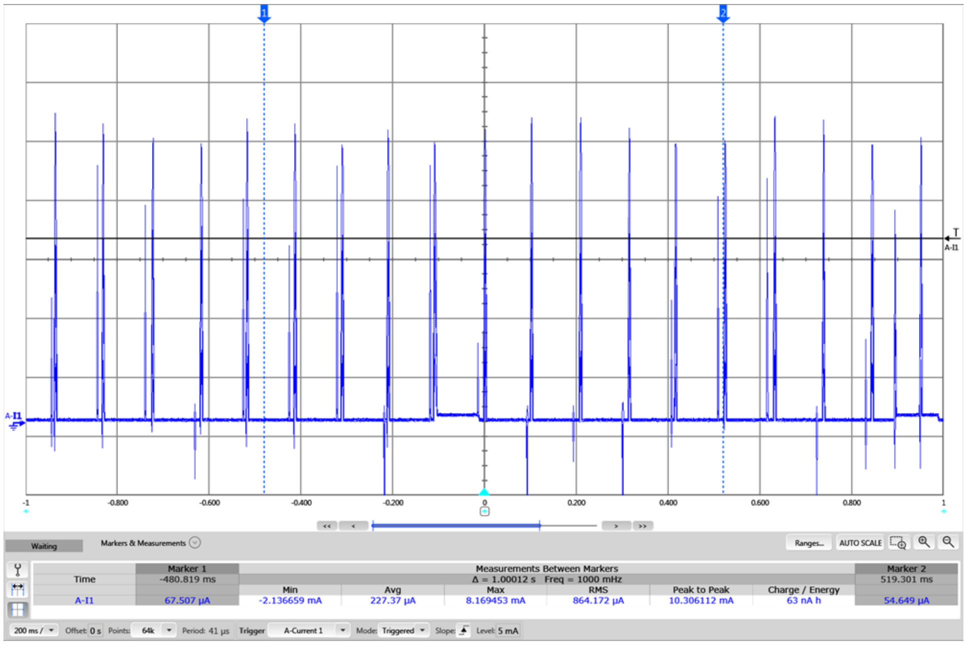
Figure 15. Start-Up Current Consumption



	Marker 1	Measurements Between Markers						Marker 2
Time	-101.425 ms	Δ = 102.223 ms Freq = 9.782 Hz						798 µs
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	2.661716 mA	-652.57 µA	299.99 µA	11.126914 mA	1.206145 mA	11.779484 mA	9 nA h	4.102943 mA

100 ms / Offset: 0 s Points: 16k Period: 61 µs Trigger A-Current 1 Mode: Triggered Slope: Level: 6 mA

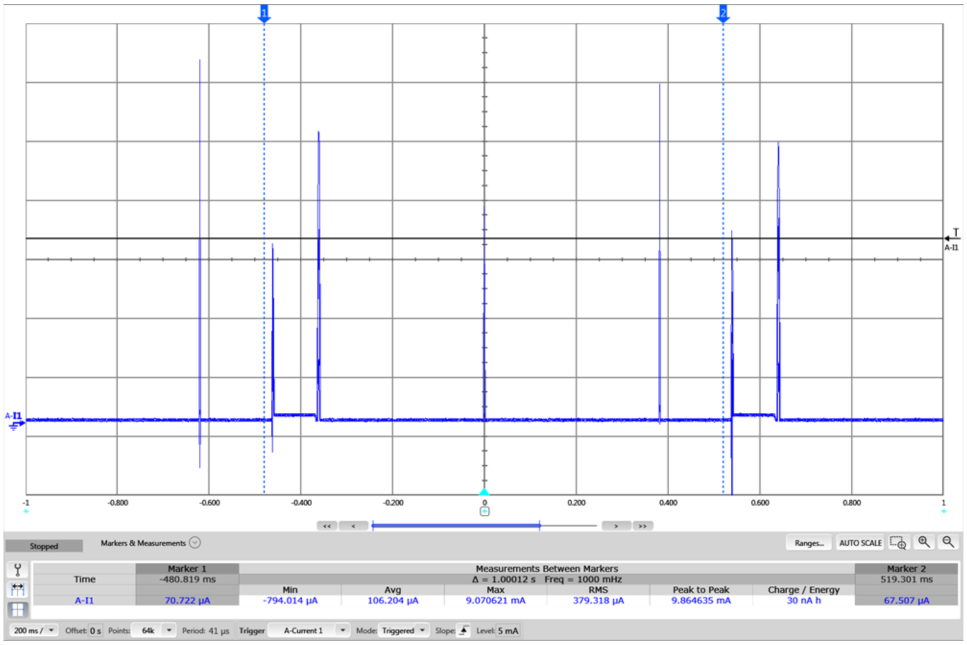
Figure 16. Auto-Advertisements Peak Current



	Marker 1	Measurements Between Markers						Marker 2
Time	-480.819 ms	Δ = 1.00012 s Freq = 1000 mHz						519.301 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	67.507 µA	-2.136659 mA	227.37 µA	8.169453 mA	864.172 µA	10.306112 mA	63 nA h	54.649 µA

200 ms / Offset: 0 s Points: 64k Period: 41 µs Trigger A-Current 1 Mode: Triggered Slope: Level: 5 mA

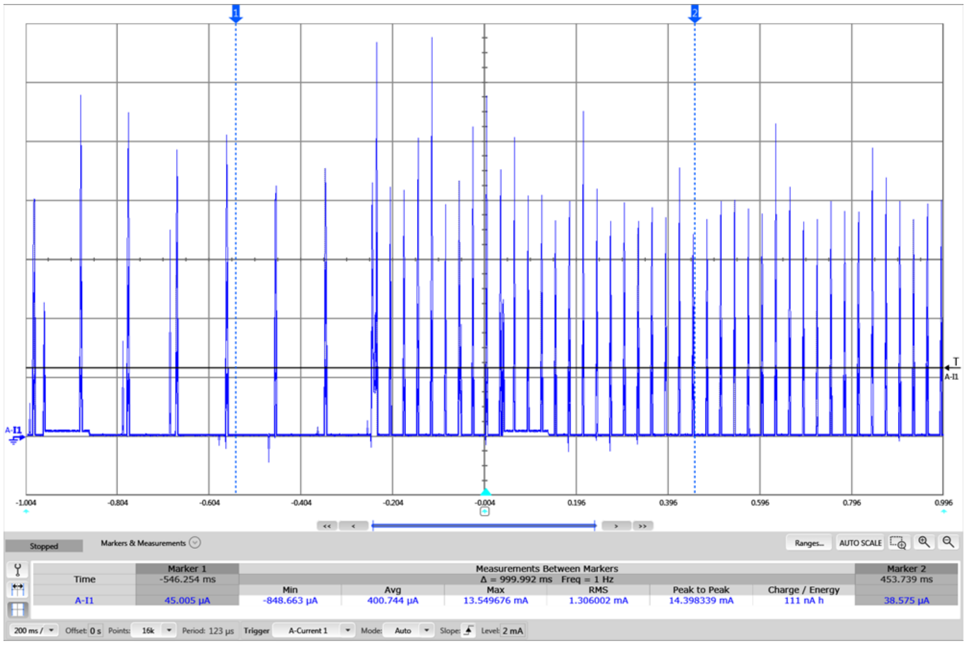
Figure 17. Average Current for 100-ms Auto-Advertisement



	Marker 1	Measurements Between Markers						Marker 2
Time	-480.819 ms	Δ = 1.00012 s Freq = 1000 mHz						519.301 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	70.722 µA	-794.014 µA	106.204 µA	9.070621 mA	379.318 µA	9.864635 mA	30 nA h	67.507 µA

200 ms / Offset: 0 s Points: 64k Period: 41 µs Trigger A-Current 1 Mode: Triggered Slope: Level: 5 mA

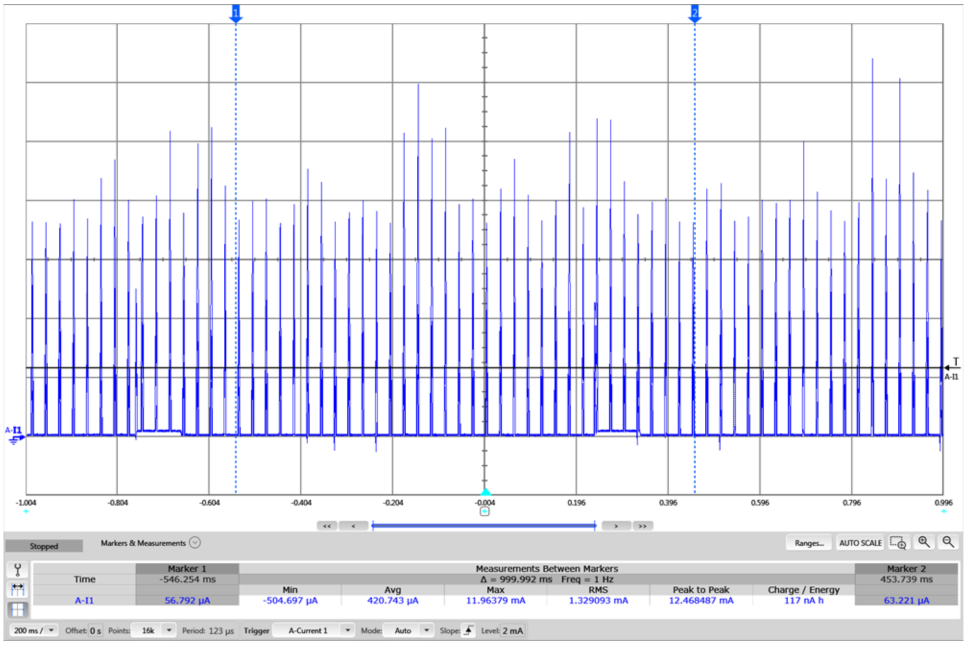
Figure 18. Average Current for 1-s Auto-Advertisement



	Marker 1	Measurements Between Markers						Marker 2
Time	-546.254 ms	Δ = 999.992 ms Freq = 1 Hz						453.739 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	45.005 µA	-848.663 µA	400.744 µA	13.549676 mA	1.306002 mA	14.398339 mA	111 nA h	38.575 µA

200 ms / Offset: 0 s Points: 16k Period: 123 µs Trigger A-Current 1 Mode: Auto Slope: Level: 2 mA

Figure 19. Current Consumption Change From Unconnected Auto-Advertisement to Connected



	Marker 1	Measurements Between Markers						Marker 2
Time	-546.254 ms	Δ = 999.992 ms Freq = 1 Hz						453.739 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	
A-I1	56.792 µA	-504.697 µA	420.743 µA	11.96379 mA	1.329093 mA	12.468487 mA	117 nA h	63.221 µA

200 ms / Offset: 0 s Points: 16k Period: 123 µs Trigger A-Current 1 Mode: Auto Slope: Level: 2 mA

Figure 20. Average Current Consumption When Connected to a Smart Device

3.2.2.2 Range

When the patch was worn, the temperature read from an android app was determined to have a signal strength of roughly –48 to –50 dBm at extreme close range. This translates to an expected range of roughly 12 meters (39 feet) in open air. In practice, this range was found to be around 40 feet for the patch under test when communicating to the SimpleLink SDK Explorer app through auto-advertisement. The only information transmitted was the temperature, therefore the app could be continuously updated without the need for an actual BLE connection between the patch and smart device. Range in practical designs will always vary based on obstacles in the RF signal path, position of the wearer, and radiated output power. If longer range is desired, a protocol other than BLE can be employed in a similar manner.

3.2.2.3 System Accuracy

In total, 10 patches were tested for accuracy within the liquid oil-bath. The results are given in Figure 21. The patches were assessed to be well within the specified ASTM requirements for medical-grade accuracy given in Table 2, therefore no additional calibration was applied to the TMP117's offset register. For products actually intended for use in a medical setting, packaging must be included during accuracy testing to ensure total system accuracy.

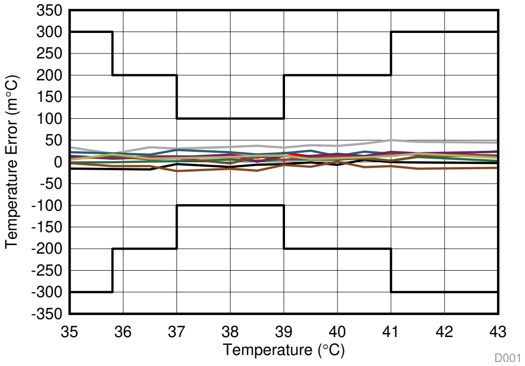


Figure 21. Results of Patch Temperature Accuracy Testing. ASTM Limits are Shown in Black

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01624.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01624.

4.3 PCB Layout Recommendations

The layout for the flex PCB patch was done on a two-layer board, with the intention of maximizing overall board flexibility. Higher numbers of layers will likely limit the bending radius of the board and affect wearer comfort. For general recommendations for flex PCBs, designers should consult with the desired manufacturer of their flex board. These boards are extremely thin, therefore they can be sensitive to heat applied during the process of soldering or reflow. It is important that this aspect be considered to minimize potential damage to the board traces. If reliability is a concern, consider applying a semi-rigid design form factor by applying a stiffener to portions of the board not intended to bend. This design uses a stiffener on the front side of the board, opposite of the TMP117 in order to lengthen the life-span of the vias surrounding the sensor

4.3.1 Layout Considerations for the CC2640R2F

The CC2640R2F, along with the RF matching network and antenna, will require a large copper pour on the bottom layer of the board to provide a low impedance path to ground. In a two-layer design, this means that only the top layer is available to route signals to and from the CC2640R2F. Take care to ensure that the necessary bypass components are still placed as close to the IC as possible. Multiple vias underneath the CC2640R2F provide a low impedance path to ground for the device itself. Figure 22 shows the CC2640R2F footprint and wiring on the flex PCB.

Remember to consider the width of the signal traces to the balun and RF antenna in two-layer design cases. With the most rigid PCBs, it is often possible to find reasonable width traces that provide matching to design impedances. In the case of a 2-layer design, the thickness of the board, the PCB design rules, and the desired cost of the boards will limit the maximum characteristic impedance of these traces. If matching is not possible, TI recommends to keep these traces as short as possible. Additionally, a pi-type matching network using 0201 footprints was left to allow matching with lumped elements. RF Impedance matching should be performed with the patch adhered to a wearer's skin to emulate the environment of use.

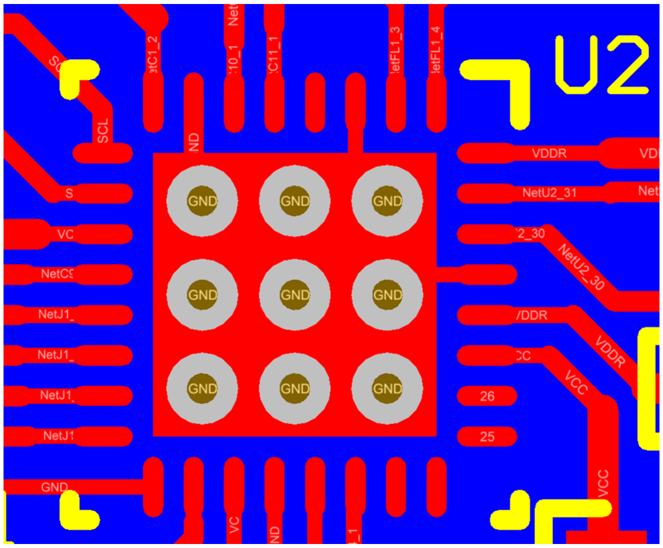


Figure 22. CC2640R2F Routing on 2-Layer Flex Patch With Ground Plane Shown in Blue

4.3.2 Layout Considerations for the TMP117

4.3.2.1 WCSP (YBG) Package

Revision B of the Bluetooth-Enabled High Accuracy Skin Temperature Measurement Flex PCB Patch uses the TMP117AIYBGR to demonstrate one potential technique for measuring skin temperature. In this design, the WCSP version of the TMP117 has the coated backside placed directly against the skin of the wearer, and heat is conducted from the skin directly to the TMP117. In an end system that uses this technique the TMP117 can be covered in a soft overmolding to protect the device from damage.

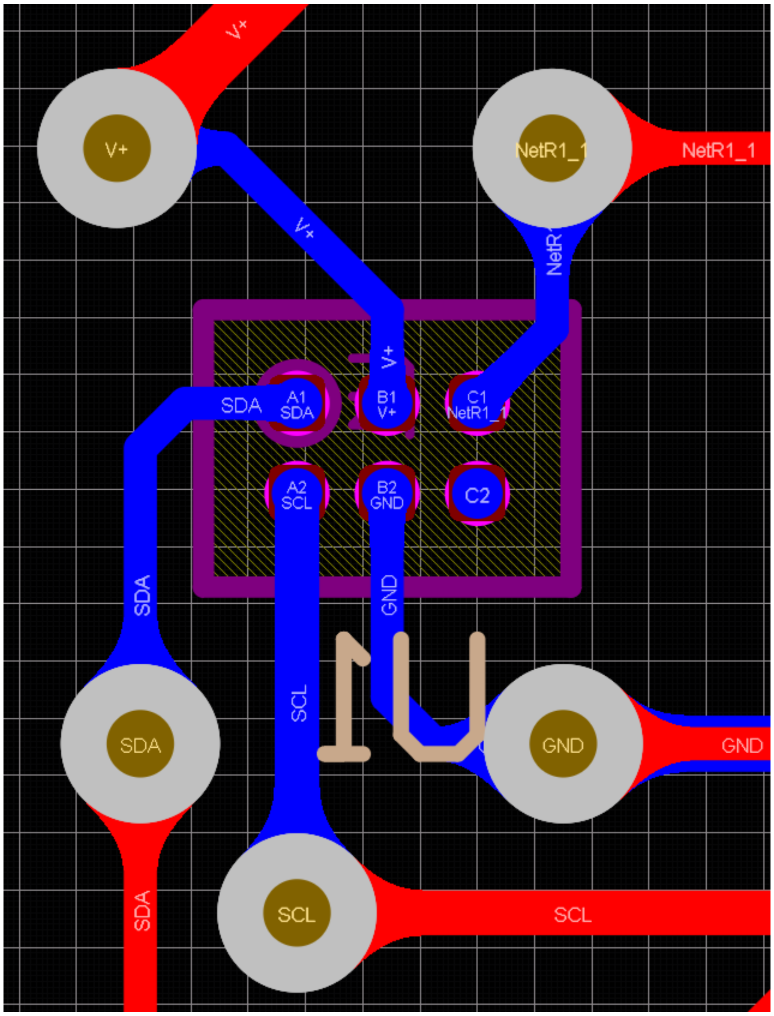


Figure 23. TMP117AIYBGR layout as it appears in PCB Editor. The TMP117 is located on the skin side of the patch. All vias have at least 30 mil clearance from the edge of stiffener on the topside of the board.

This technique can be modified for applications that use enclosures but still want to measure skin temperature such as smartwatches or earbuds. The TMP117 can be placed against a metal contact to conduct heat from the wearer's skin, as shown in Figure 24. Alternatively, the underside of the device can be used to transfer heat as shown in Figure 25. If using the underside of the package, consider using a board stiffener made of a biocompatible and thermally conductive material such as stainless steel.

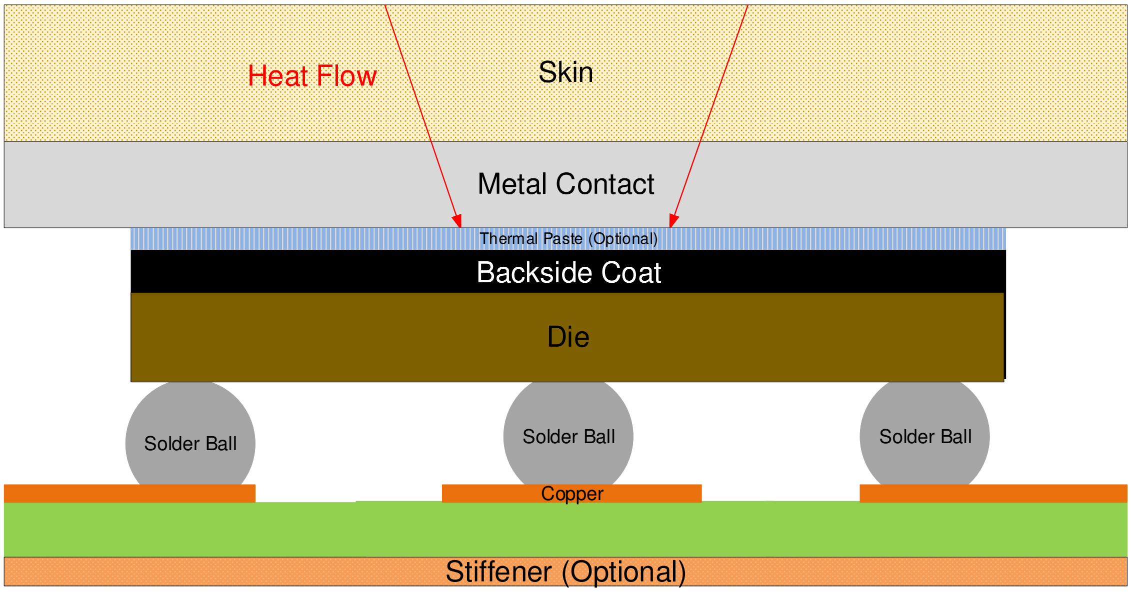


Figure 24. Example stack-up for external case sensing using top side of TMP117 in WCSP package

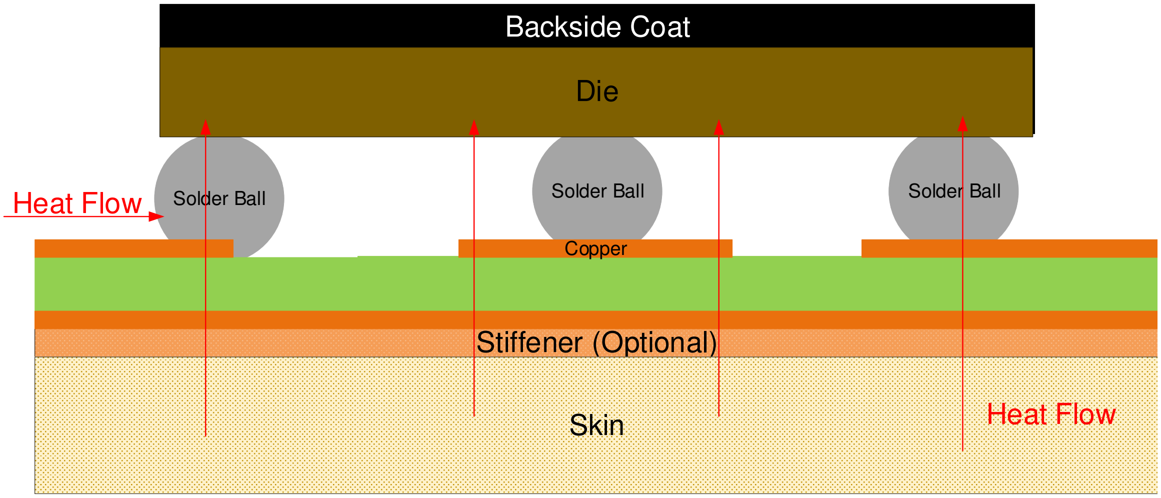


Figure 25. Example stackup for sensing from underside of TMP117 in WCSP Package

4.3.2.2 WSON (DRV) Package

For high-accuracy measurements with the WSON package, the recommendations within the *Precise temperature measurements with the TMP116 and TMP117* (SNOA986) should be followed. Similar to the WCSP package, the WSON package may be used for sensing from either the top or bottom sides.

Figure 26 shows how heat will flow into a WSON package when using the bottom side of the package to make skin contact. If on a flex board of 12 mils thickness or below, the thermal pad under the device should be soldered down. If on a rigid board, the thermal pad should be left unconnected. The air-gap between the thermal pad and the copper plane on bottom is not expected to noticeably affect the thermal response because of the low thermal mass of the TMP117.

Figure 27 shows the heat flow through a WSON package when the topside of the device is being used for contact measurements. When pressing against a metal contact, the presence of thermal paste is beneficial if it improves mechanical contact between the TMP117 and contact pad. If good mechanical contact can be guaranteed without thermal adhesive, it can be omitted to reduce thermal mass.

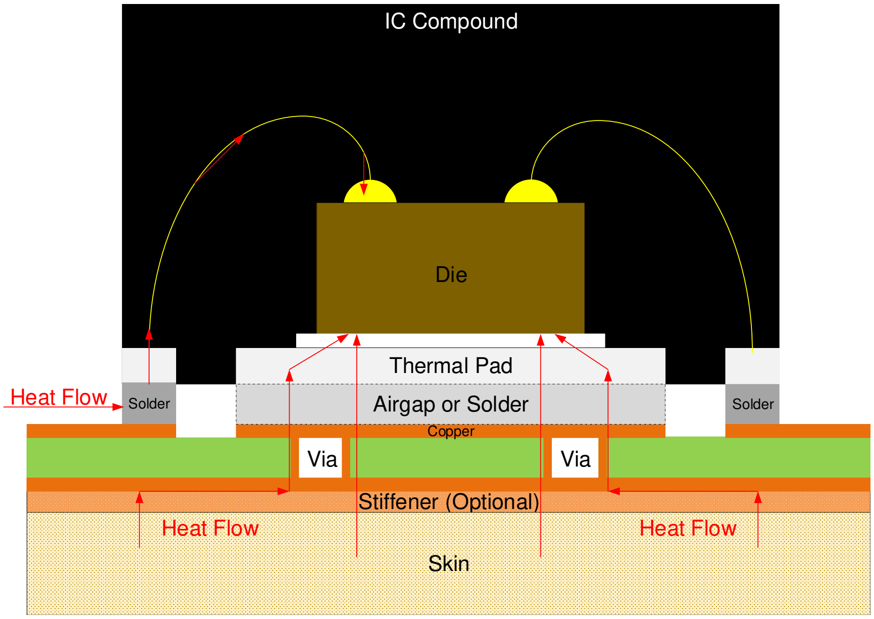


Figure 26. Heat Flow Through TMP117 in WSON Package

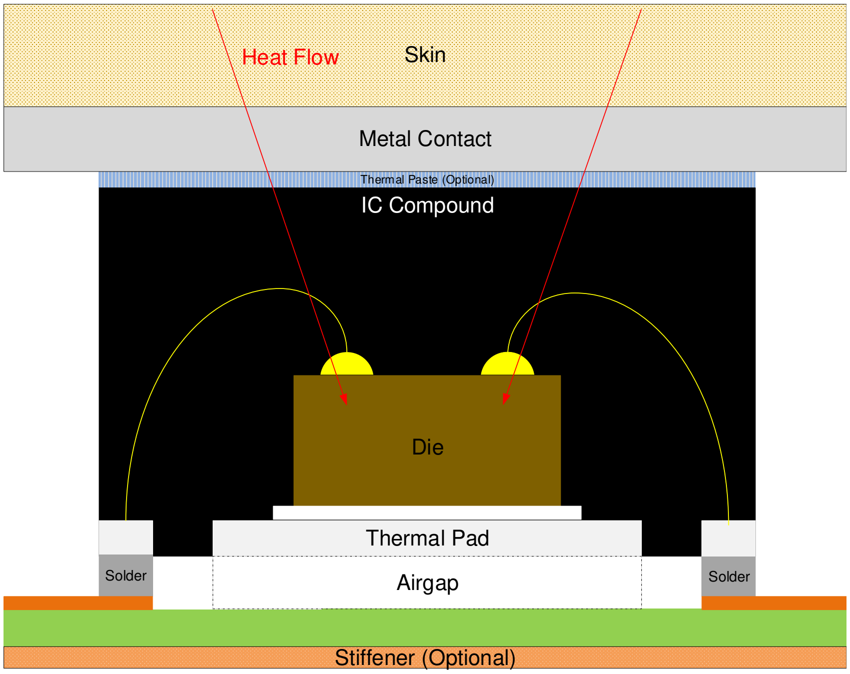


Figure 27. Example stackup for external case sensing using the top side of the TMP117 in WSON package.

4.3.3 Layout Prints

To download the layer plots, see the design files at TIDA-01624.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01624.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01624.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01624.

5 Software Files

To download the software files, see the design files at TIDA-01624.

6 Related Documentation

1. Texas Instruments, *CC26x0 SimpleLink™ Bluetooth® low energy software stack 2.2.x developer's guide* (SWRU393)
2. Texas Instruments, *CC13x0, CC26x0 SimpleLink™ wireless MCU technical reference manual* (SWCU117)
3. Texas Instruments, *TMP117 High-accuracy, low-power, digital temperature sensor* (SNOSD82)
4. Texas Instruments, *Layout considerations for wearable temperature sensing* (SNOAA03)
5. Texas Instruments, *Design challenges of wireless patient temperature monitors* (SNOAA07)
6. Texas Instruments, *Precise temperature measurements with the TMP116* (SNOA986)

6.1 Trademarks

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Revision History

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

Changes from Original (January 2019) to A Revision	Page
• Changed board layout image reflecting new patch design	1
• Changed text to reflect new patch layout	3
• Changed image to reflect new patch design	6
• Deleted the following images: Setup for Programming of the Patch; Reading From the Patch. Only the Patch and a Smart phone are Required; Current Consumption Testing Setup.Power Analyzer Used to Supply3-V Power to Patches Under Test; Test Setup for Temperature Accuracy Testing of the TMP117FlexPatch; Stirred Liquid Baths Provide Very Uniform Thermal Environments	12
• Changed tests	20
• Added WCSP (YBG) Package and WSON (DRV) Package sections	21
• Changed image: TMP117AIYBGR layout as it appears in PCB Editor. The TMP117 is located on the skin side of the patch. All vias have at least 30 mil clearance from the edge of stiffener on the topside of the board	21

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