

TI Designs: TIDA-01624

支持蓝牙技术®的高精度体温测量柔性 PCB 贴片参考设计



说明

此参考设计演示了借助 CC2640R2F 无线 MCU 使用 TMP117 高精度数字温度传感器进行体温高精度感应。此用户指南与评估软件和智能设备应用搭配使用，可为医疗和可穿戴应用中的体温测量提供设计指导。

资源

TIDA-01624

设计文件夹

TMP117

产品文件夹

CC2640R2F

产品文件夹



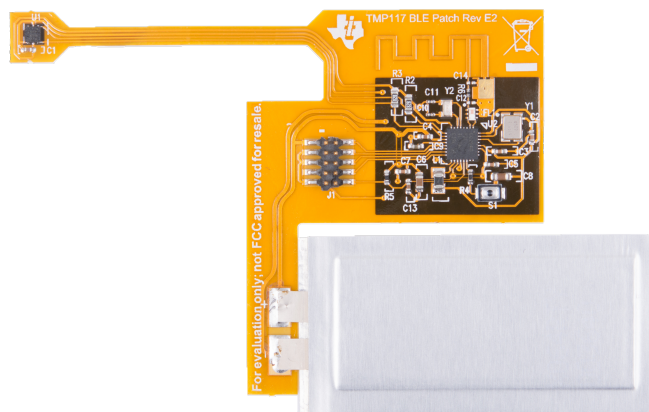
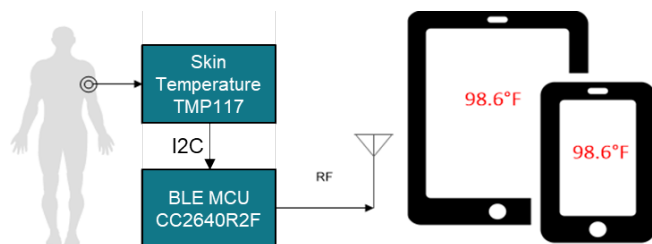
咨询我们的 E2E™ 专家

特性

- 高精度 ($\pm 0.1^{\circ}\text{C}$) 人体温度测量
- 2.4GHz 射频收发器 与®低功耗蓝牙 (BLE) 4.2 和 5 规范兼容
- 集成的 PCB 天线
- PCB 设计灵活
- 高达 3 年的货架期以及 5 天的活动时间
- 用于设备监控的 iOS 应用

应用

- 医疗设备
- 医疗保健
- 可穿戴设备



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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 smartphone 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 operates on a 3-V, flexible thin-film battery, which is made possible due to the 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 3-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

表 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 | −40°C to +85°C | Limited by operating range of CC2640R2 |
| Temperature accuracy | ±0.1°C (max) from +35°C to +43°C | 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

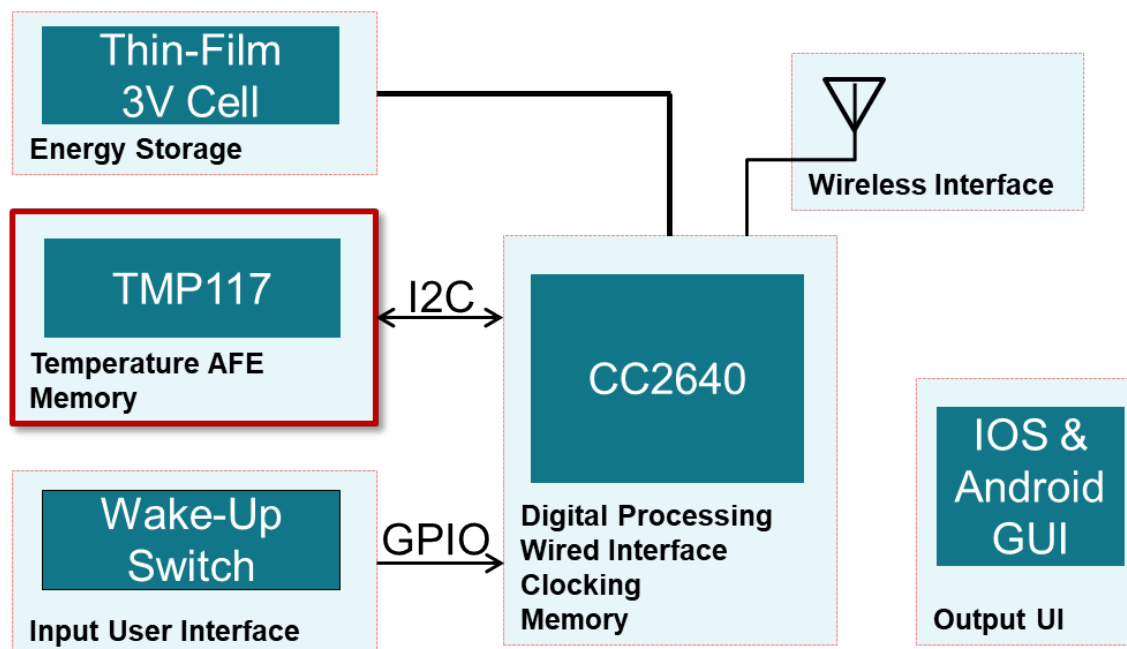


图 1. TIDA-01624 Block Diagram

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 98.6°F, 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 (1°F) lower than that of an oral thermometer.

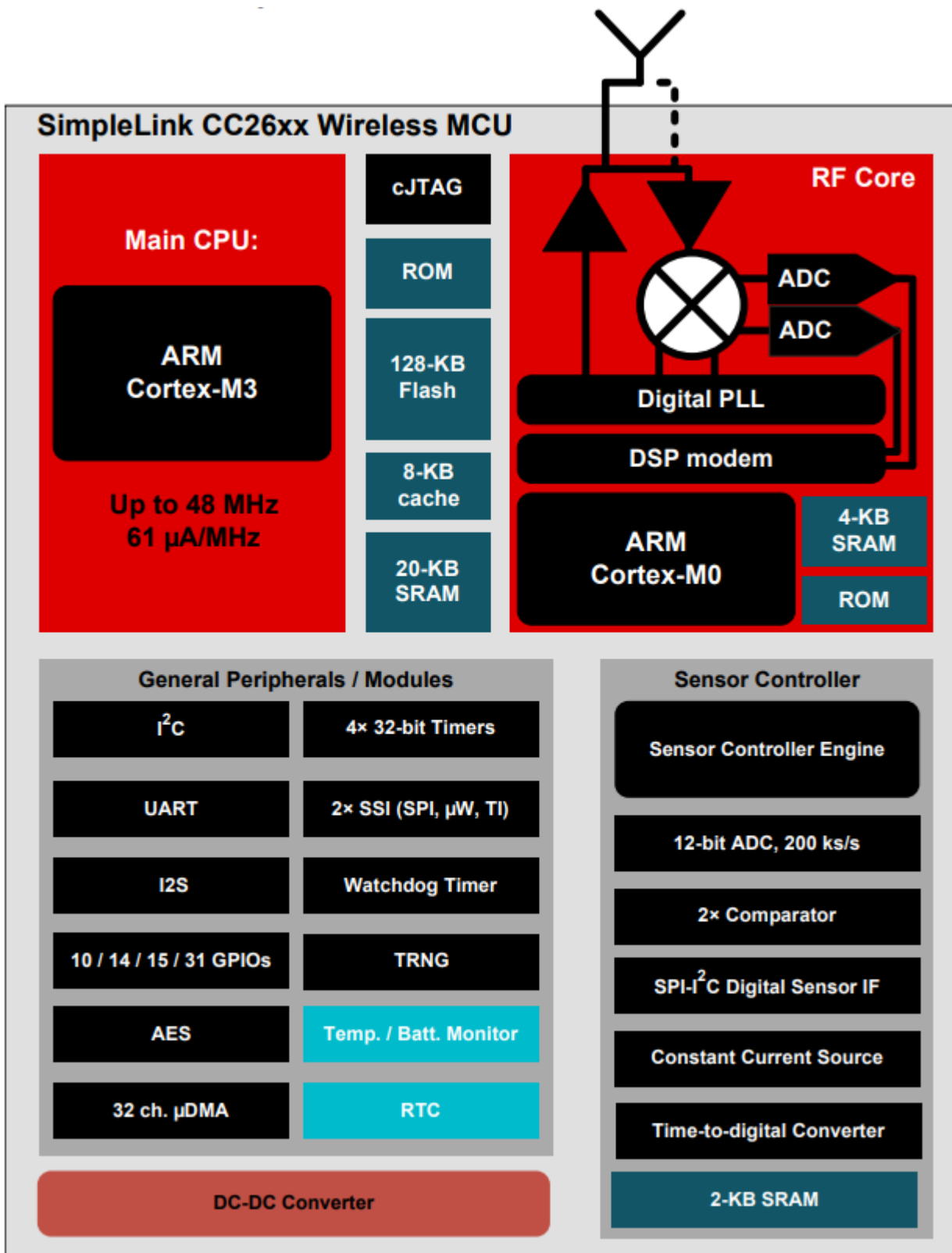
The crucial distinction here is between *core temperature* and *skin temperature*. The primary goal of this design is to demonstrate effective techniques for the measurement of skin temperature. The temperature at the surface of a patient's skin will not normally be identical to their core temperature. 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.

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 technique which can be employed for underarm measurements. Extending the TMP117 away from the primary portion of the board that contains the RF antenna not only thermally isolates the device, but also allows the RF antenna to be exposed on one side while the sensor is enclosed underneath the user's arm. In production systems that use axillary measurements, users can move this long flexible arm to place the antenna in an area that can ensure RF performance.

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.



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图 3. CC640R2F Block Diagram

2.4 System Design Theory

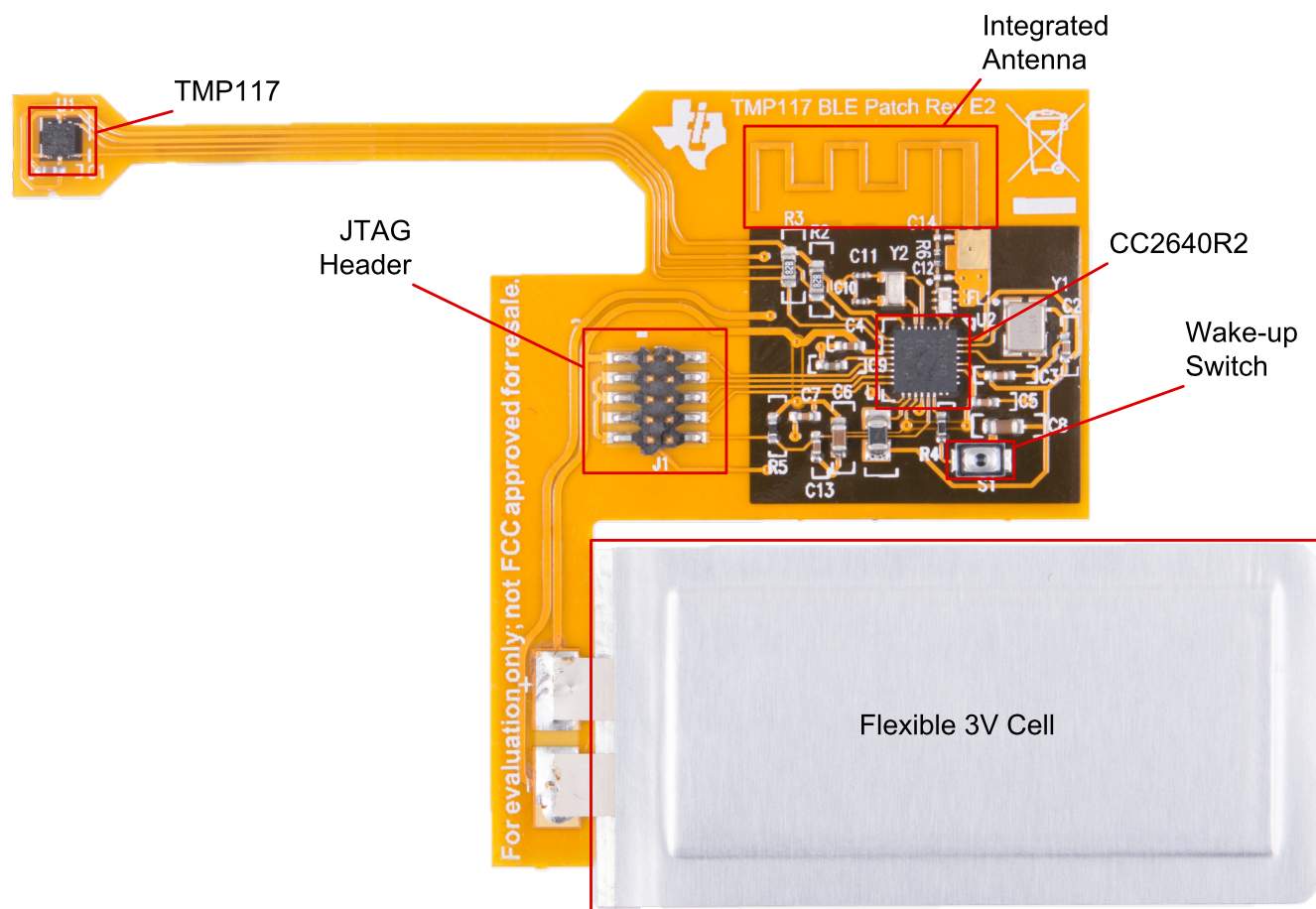


图 4. Key Features in Design Layout

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 shelf life of the battery itself and not by the charge storage.

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. 节 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.

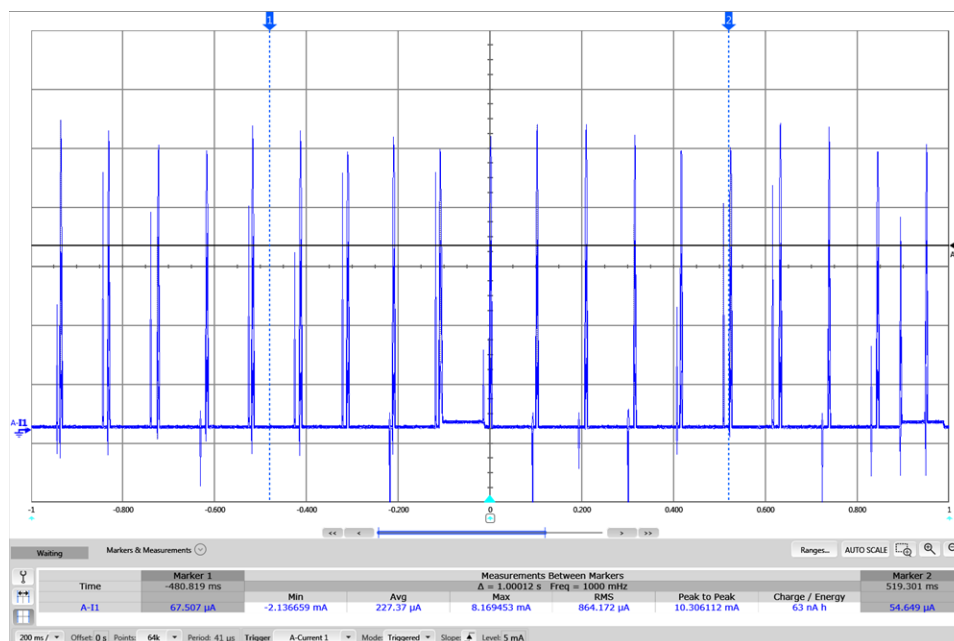


图 5. Power Meter Capture of Current Draw During 10-Hz Auto-Advertisement

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. 节 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 is 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. 表 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 specify 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 表 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.

表 2. Temperature Accuracy Requirements Under ASTM E1112

| Temperature (°C) | Maximum Error (°C) |
|------------------|--------------------|
| < 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 smartphone 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 smartphone 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 .

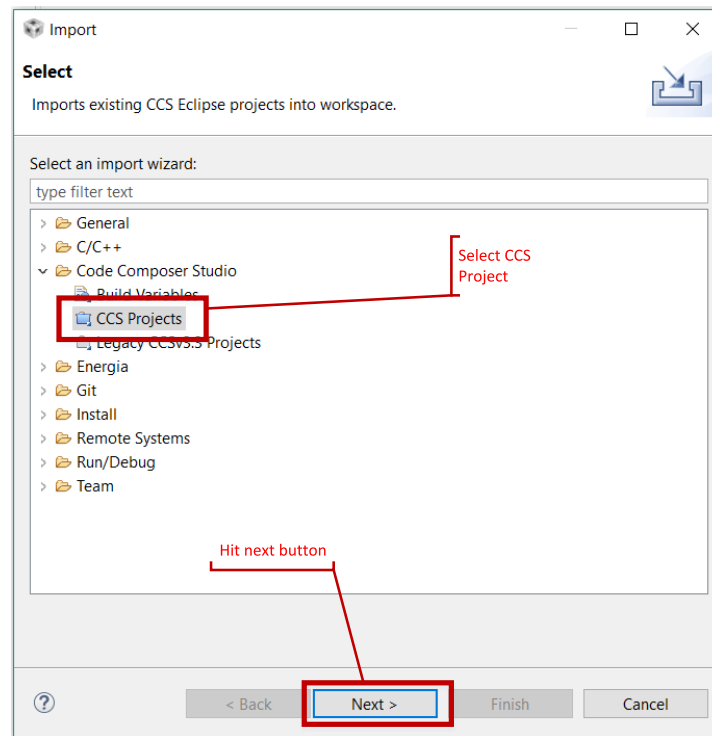


图 6. Software Import Menu

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

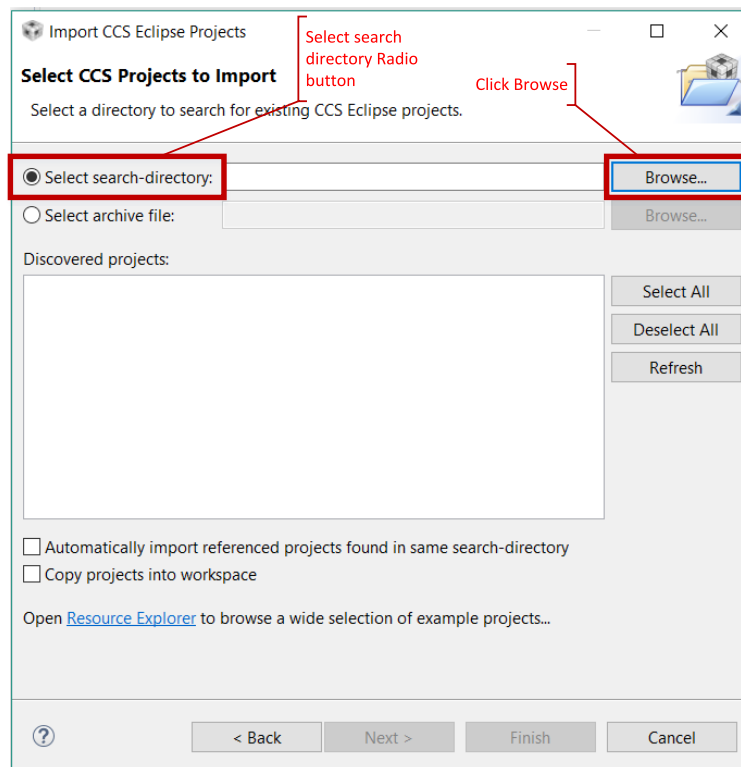


图 7. Import Project Menu

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

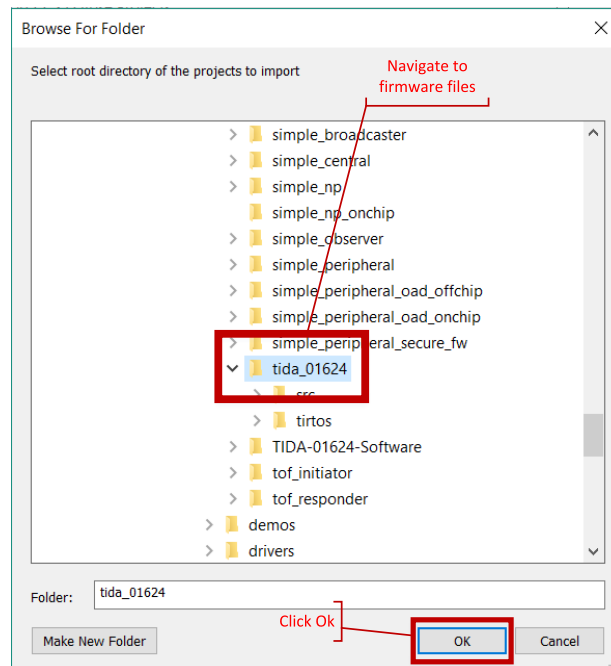


图 8. Project Browser

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

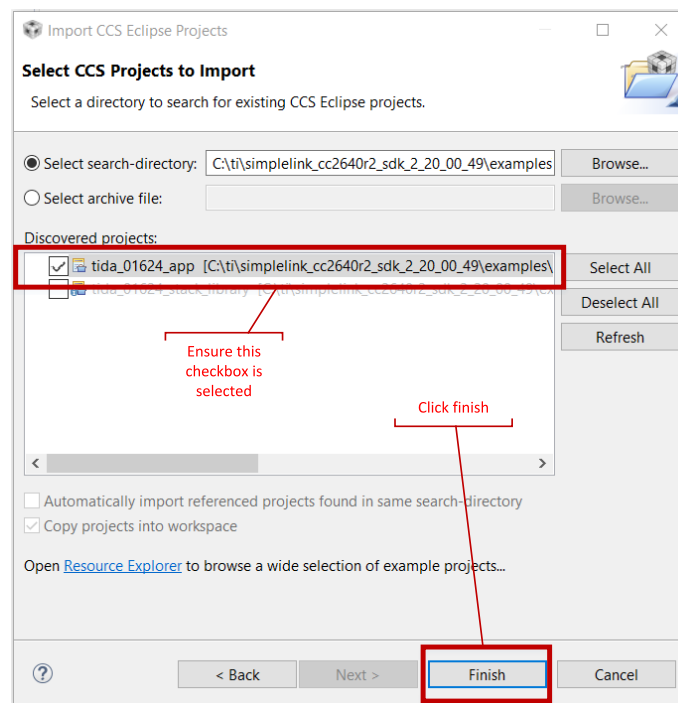


图 9. CCS Project Importing

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

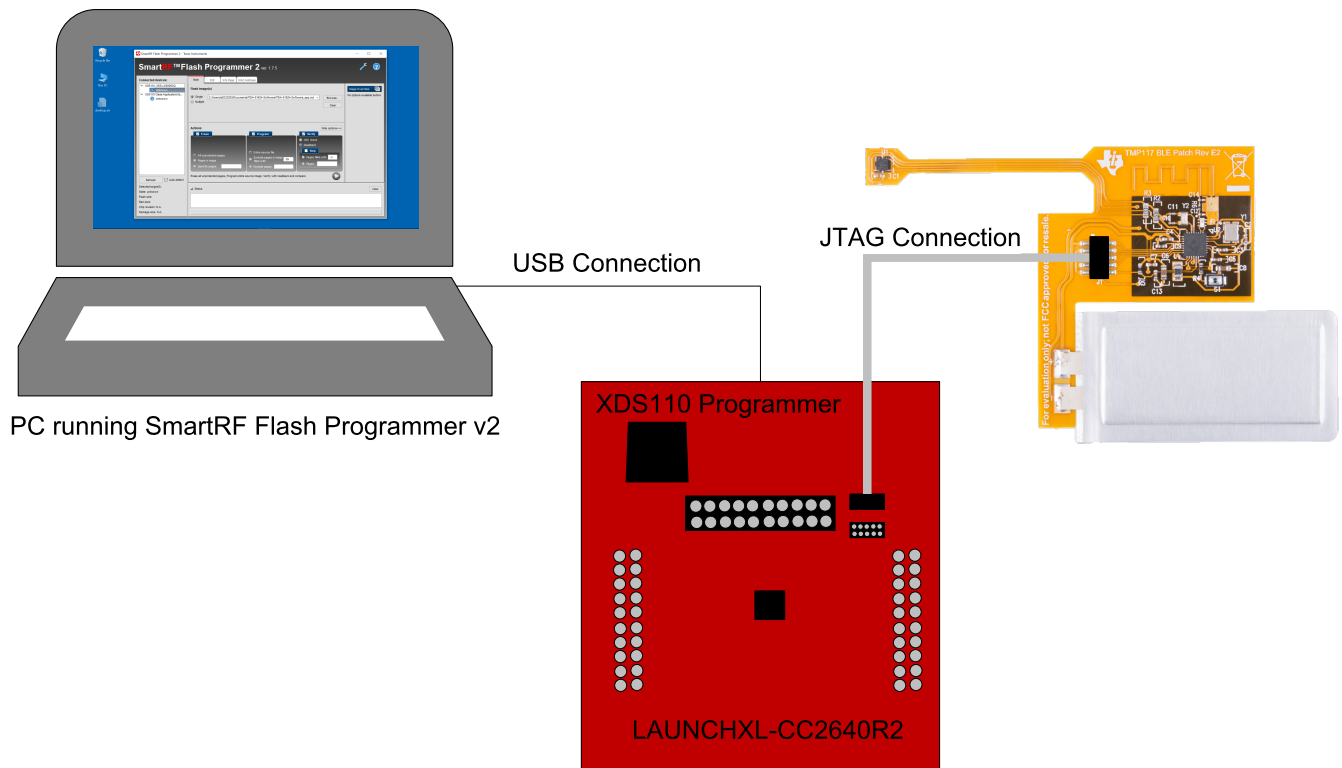


图 10. Setup for Programming of the Patch

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 the 10-pin ribbon cable that comes with the Launchpad (see 图 10).

After configuring the LaunchPad, the designer can click on the Debug button shown in to download the firmware using CCSv8.2. 图 11.

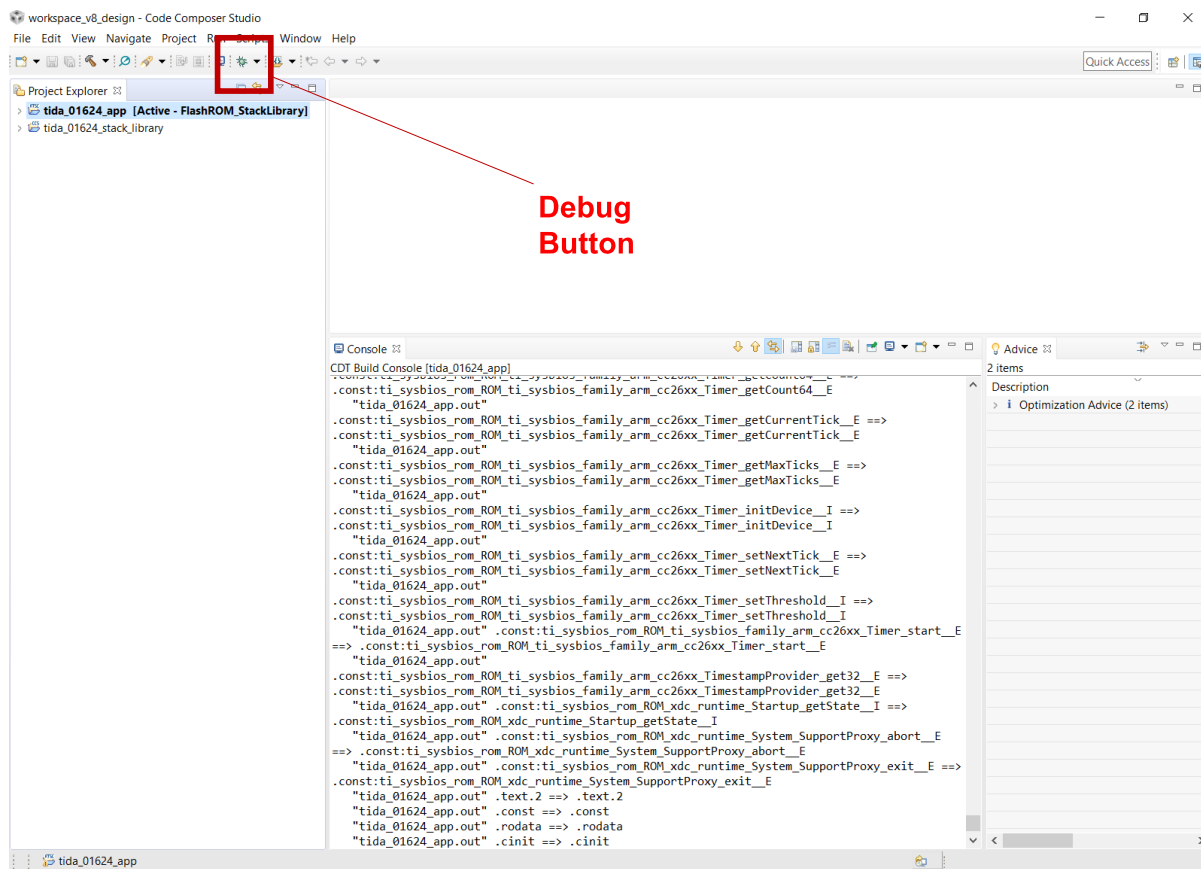


图 11. Downloading Firmware to the CC2640R2.

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. 图 12 shows the setup for reading from the patch through a smartphone, and 图 13 to 图 16 shows how to navigate the SimpleLink SDK Explorer app.

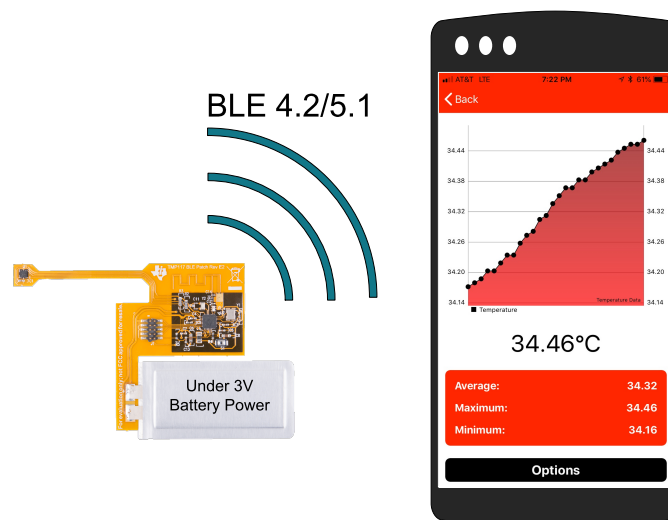


图 12. Reading From the Patch. Only the Patch and a Smartphone are Required.

1. On start-up, Simplelink SDK Explorer will default to the standard SDK BLE Plugin (see 图 13). You can change this by selecting the SDK BLE Plugin under "Current Product".

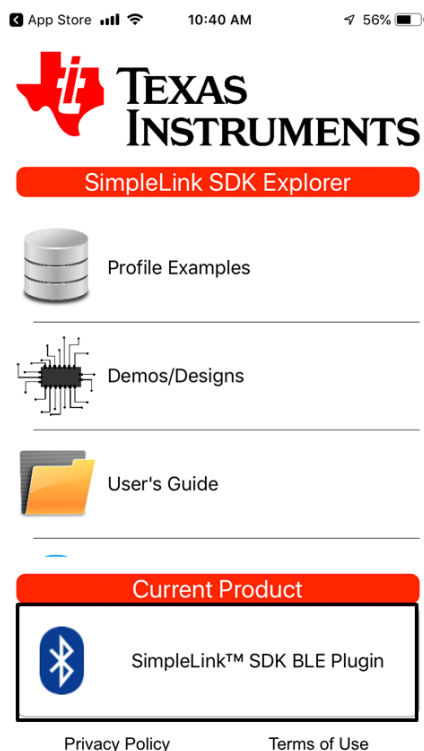


图 13. SimpleLink SDK Explorer Main Page

2. Select "TI Sensing Solutions" under the list of products

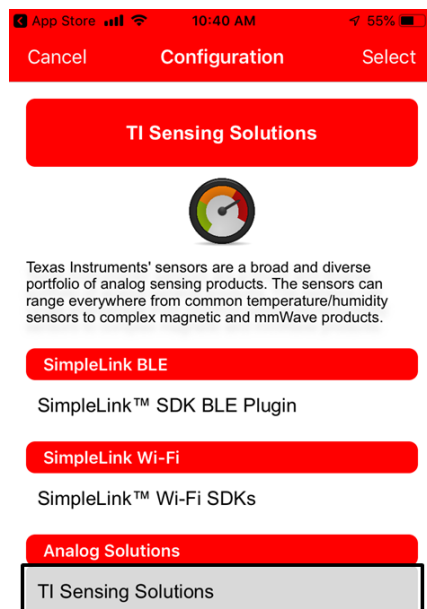


图 14. TI Sensing Solutions

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

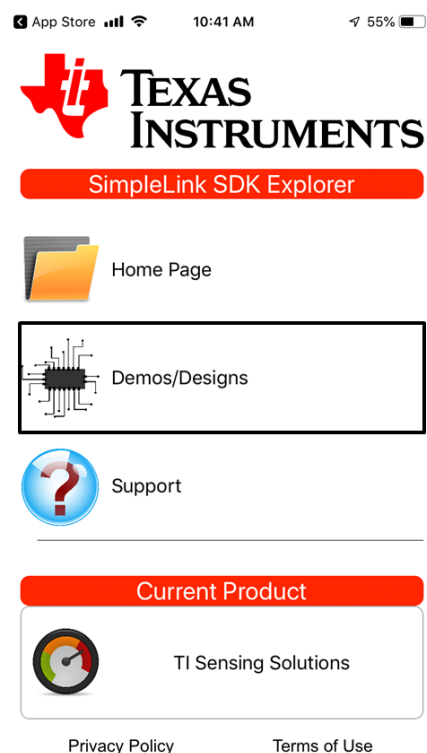


图 15. Home Page With the TI Sensing Solutions Product Selected

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

Patch.

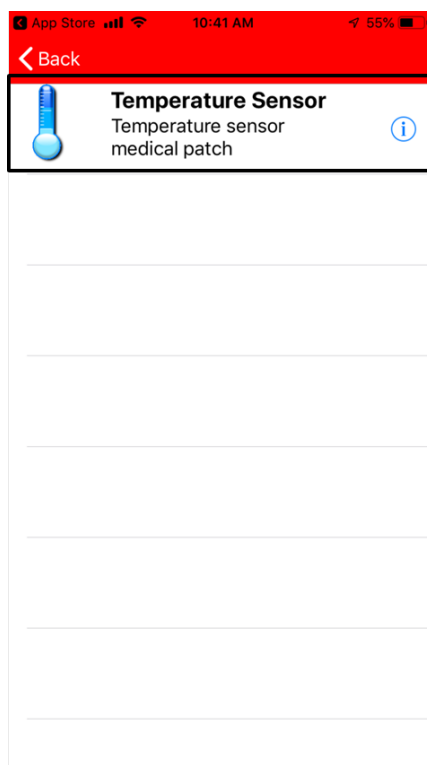


图 16. Temperature Sensor Medical Patch Demo. Select to Search for Patches in the Area.

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.

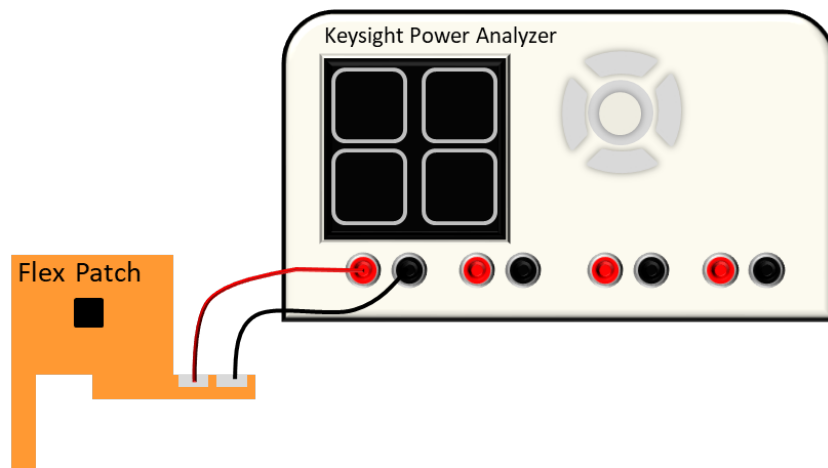


图 17. Current Consumption Testing Setup. Power Analyzer Used to Supply 3-V Power to Patches Under Test.

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 smartphone, 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. This setup is shown in 图 18.

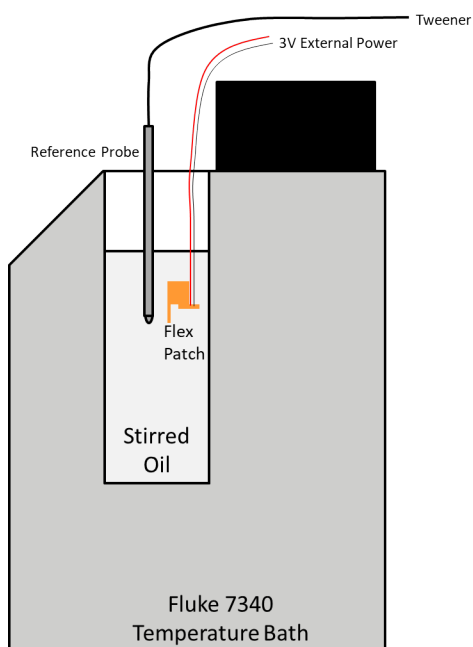


图 18. Test Setup for Temperature Accuracy Testing of the TMP117 Flex Patch. Stirred Liquid Baths Provide Very Uniform Thermal Environments.

3.2.2 Test Results

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

3.2.2.1 Current Consumption/Life-Span

图 19 到 图 24 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 μ A, 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. 公式 1 shows how to estimate the patch lifetime depending on the total connection period.

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

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.
- $I_{\text{Connected}}$ and I_{Active} are the average current consumption (in mA) of the design when connected to a smart device, and when auto-advertising.

(1)

表 3. Average Current Consumption

| Condition | Measured Current Draw | Associated Figure | Expected Runtime |
|-----------------------------------|-----------------------------|-------------------|---------------------------|
| Initial Startup | 3.8 mA (Avg) for 21 μ s | 图 19 | N/A |
| During Auto-Advertisement | 11.1 mA (Peak) | 图 20 | N/A |
| 100 ms (10 Hz) Auto-Advertisement | 227.37 μ A (Avg) | 图 21 | 153.93 hours, or 6.4 days |

表 3. Average Current Consumption (continued)

| Condition | Measured Current Draw | Associated Figure | Expected Runtime |
|---------------------------------|-----------------------|-------------------|---------------------------|
| 1 Sec (1 Hz) Auto-Advertisement | 106.204 μ A (Avg) | 图 22 | 329.6 hours, or 13.7 days |
| Connected to Smart Device | 420.743 μ A (Avg) | 图 24 | 83.2 Hours, or 3.5 days |

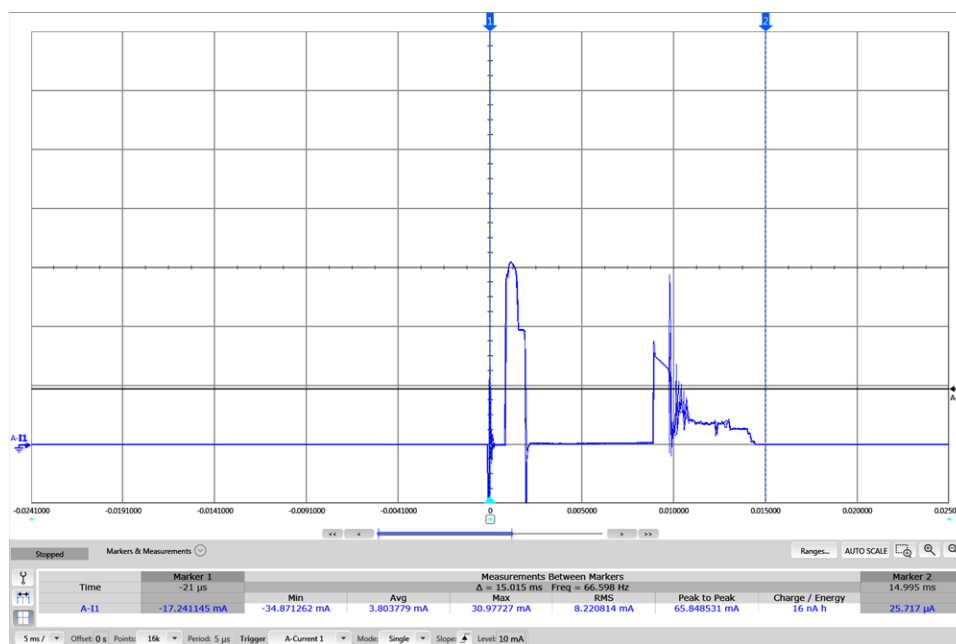


图 19. Start-Up Current Consumption

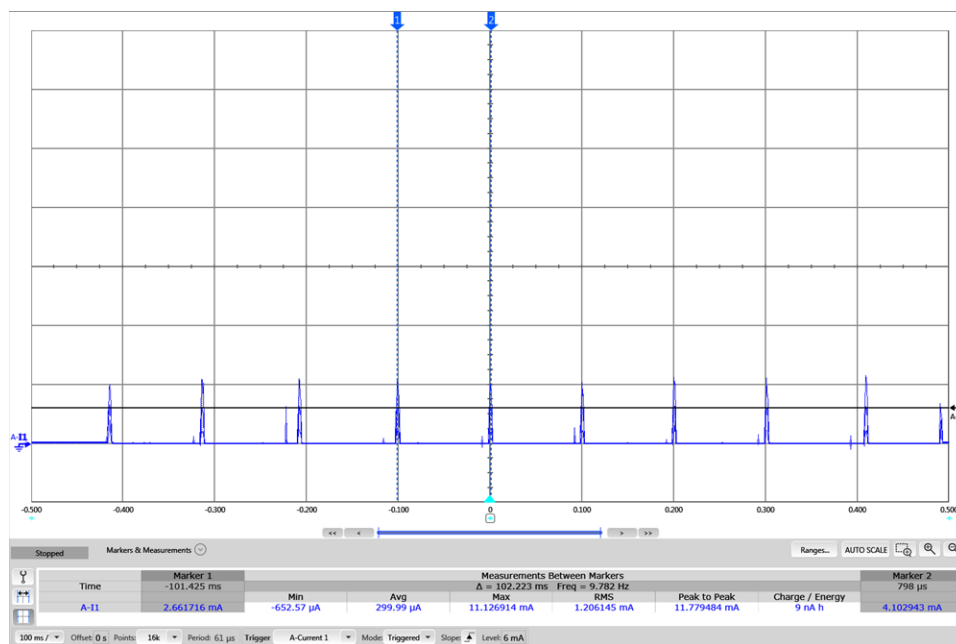


图 20. Auto-Advertisements Peak Current

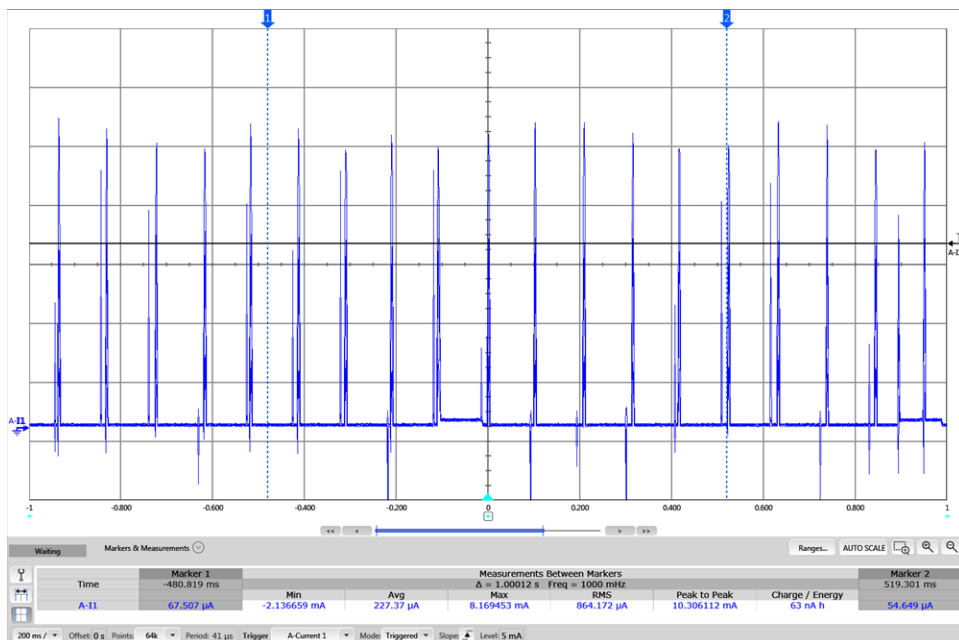


图 21. Average Current for 100-ms Auto-Advertisement

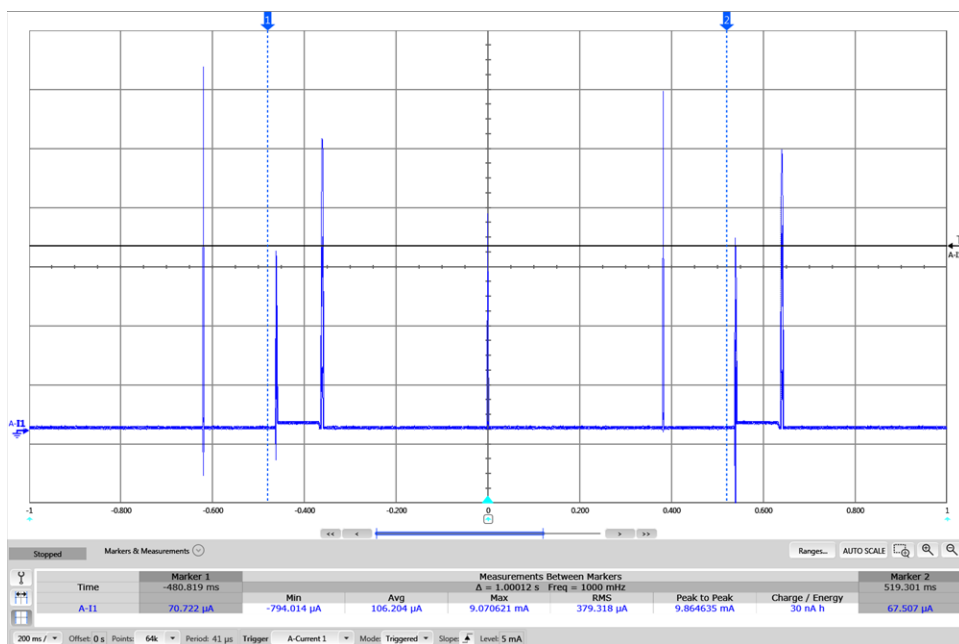


图 22. Average Current for 1-s Auto-Advertisement

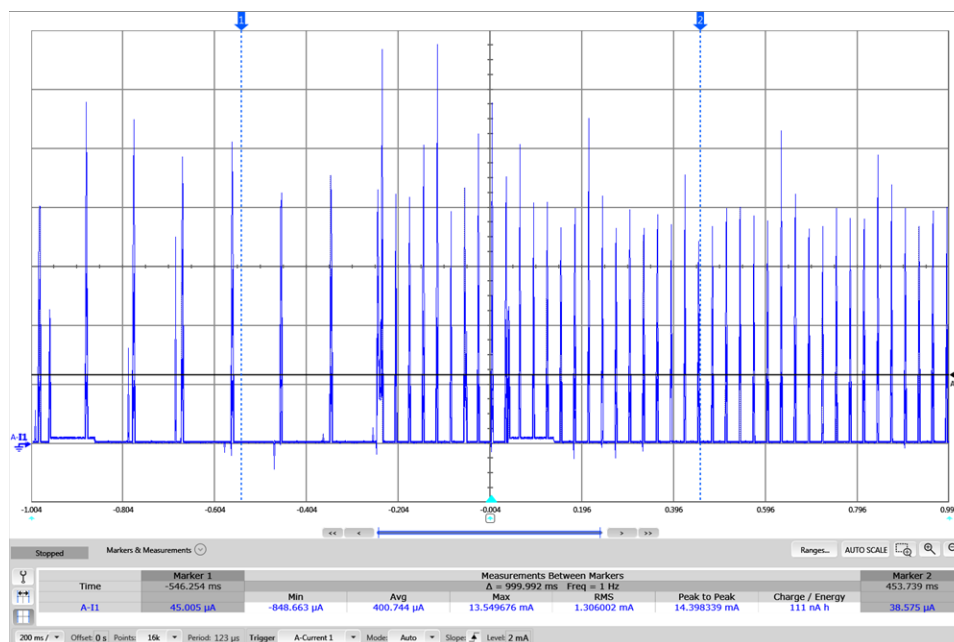


图 23. Current Consumption Change From Unconnected Auto-Advertisement to Connected.

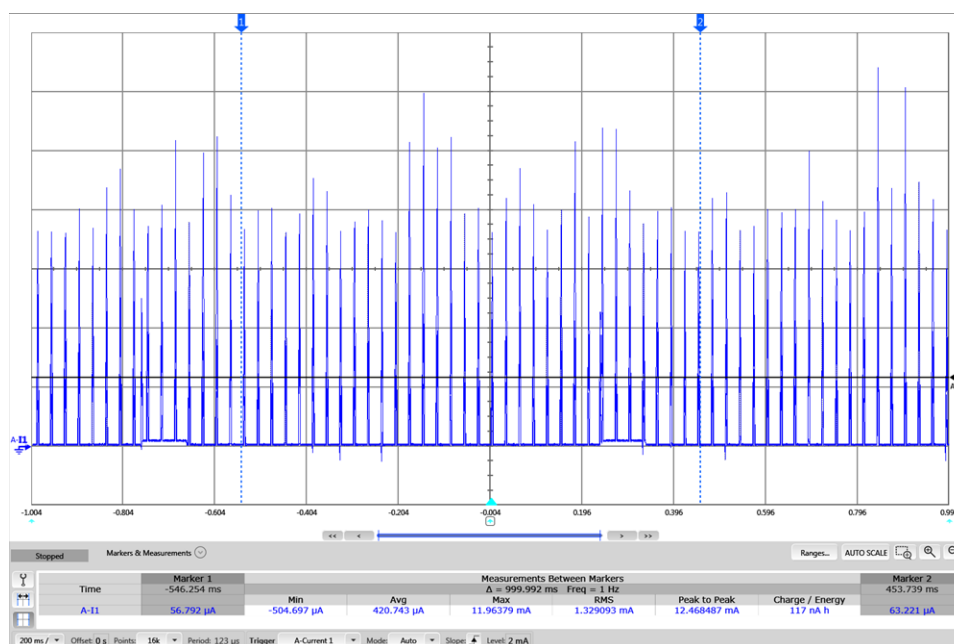


图 24. Average Current Consumption When Connected to a Smart Device.

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 图 25. The patches were assessed to be well within the specified ASTM requirements for medical-grade accuracy given in 表 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.

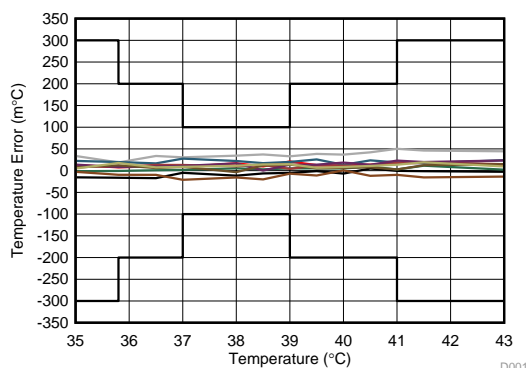


图 25. Results of Patch Temperature Accuracy Testing. ASTM Limits are Shown in Black.

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. Since the primary goal of this design is temperature measurement, the tech note [Layout considerations for wearable temperature sensing](#) (SNOAA03) provides a concise summary and explanation of many of the techniques employed. 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 the back of the active portion of the board.

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. [图 26](#) 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.



To ensure that the solder flows evenly to the TMP117 pins and directly under the package (while not flowing to the thermal pad), a keep out area must be placed around the package. The package dimension is 2.00 × 2.00 mm, so an area of 2.60 mm × 2.60 mm has been established. There should not be any coverlay/overlay material in this area to prevent solder reflow issues on the TMP117 pins. These instructions are included in the fabrication notes to help guide the PCB manufacturer.

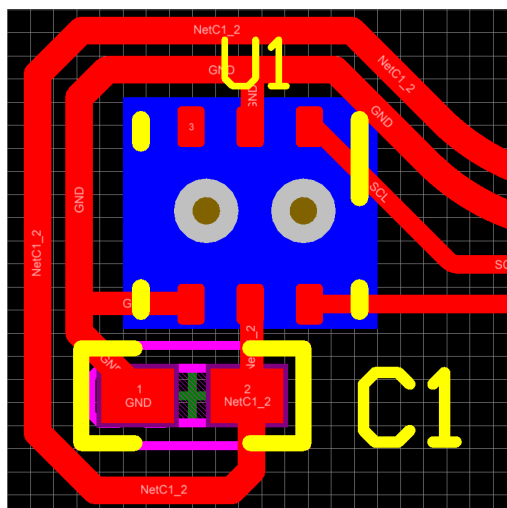


图 27. TMP117 (U1) Layout on 2-Layer Flex Board, With Bypass Capacitor (C1). Vias Conduct Heat Through the Exposed Floating Copper Pad on Bottom (Blue) and up to the Thermal Pad of the TMP117.

图 28 shows how heat flows into a WSON package such as the TMP117. 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.

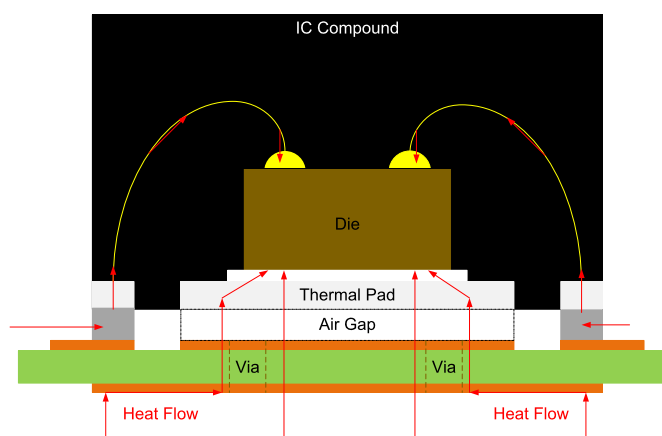


图 28. Heat Flow Through TMP117

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)

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