

Design Guide: TIDA-010029

Wearable, 16-phase multi-sensor SpO₂ and heart rate monitor (HRM) reference design with Bluetooth® 5



Description

This reference design enables a wearable, optimized saturation of peripheral capillary oxygen (SpO₂) and multi-sensor, multi-wavelength optical heart rate monitor (HRM). It uses the AFE4420 device, which is a single-chip, bio-sensing front end for photoplethysmography (PPG) measurements. It supports up to four switching light-emitting diodes (LEDs) and up to four photodiodes to enable signal acquisition of up to 16 phases. The CC2640R2F device (supporting Bluetooth® low energy 4.2 and 5) transfers the measured data to a remote location. This patient-monitoring design uses a single CR3032 battery with a 30-day life cycle. Raw data is available to calculate heart rate, SpO₂, and other related parameters. 2 onboard light-emitting diodes (LEDs) identify low-battery detection and a Bluetooth connection.

Resources

TIDA-010029	Design Folder
AFE4420	Product Folder
CC2640R2F	Product Folder
TPS61099	Product Folder
TPS63036	Product Folder
TPD1E10B06	Product Folder



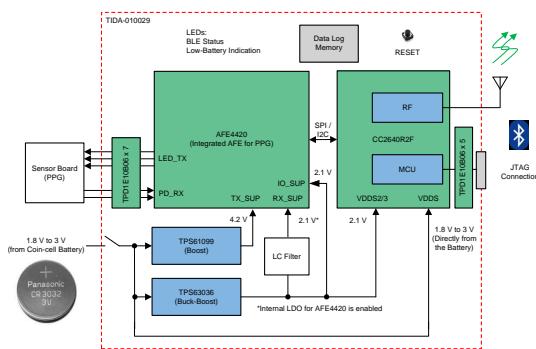
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Features

- Provides raw data to calculate heart rate, SpO₂, and other related parameters
- Uses single-chip, bio-sensing, front-end AFE4420 device for PPG measurement
 - Supports up to 4 LEDs and 4 photodiodes with ambient subtraction to improve signal-to-noise ratio (SNR)
 - Enables signal acquisition of up to 16 phases and multi-wavelength measurements with the flexible allocation of LEDs and photodiodes in each phase
- Integrated Arm® Cortex®-M3 and 2.4-GHz RF transceiver (CC2640R2F) supports wireless data transfer through Bluetooth® low energy 4.2 and 5.0
- Operates from CR3032 (3-V, 500-mA coin cell battery) with a battery life of 30 days using highly efficient DC/DC converters
- Small form factor helps in easy adaptation to wearable applications

Applications

- Pulse oximeter
- Wearable fitness and activity monitor
- Multiparameter patient monitor
- Medical sensor patches



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1 System Description

1.1 Introduction to Parameters Measured Using TIDA-010029

The TIDA-010029 device can be used to measure the following parameters: photoplethysmography (PPG), heart-rate monitoring (HRM), and peripheral capillary oxygen saturation (SpO₂).

PPG is an optical measurement of the volume of an organ. In principle, PPG illuminates the skin and subcutaneous tissue with light of a specific wavelength from a light-emitting diode (LED) to measure organ volume. This light is absorbed, passed through, or reflected back. A photodiode sensor measures the light that is either transmitted or reflected, depending on where it is placed relative to the LED. The light is then converted to an electrical signal. The information can be used to determine the heart rate of a person. PPG also provides more information about blood flow and blood pressure. This measurement can be conducted at various locations on the body to examine the blood flow to different regions. When measured closest to the aorta of the heart (for example, the left arm), some additional information can be gained regarding the cardiac output and heart valve function. One advantage that PPG has is the number of skin contacts which are required to measure it. Because PPG can be determined from reflected or transmitted light, only a single point of contact is necessary to measure it. This feature allows for easy, continuous time measurements, which is the most attractive advantage to wearable electronics such as fitness trackers.

Mostly green LEDs are used for measuring heart rates. A green LED has often been used in the reflective sensor to extract the PPG signal. Due to its wavelength, green light is known to penetrate the tissue less than higher wavelength LEDs. Hence, more unabsorbed, or reflected, light comes out of the tissue with green than with other colors. Sensing the green light from more than one powered device (PD) or eliminating from more than one LED surrounding the PD helps.

Red and infrared (IR) lights are used for pulse oximetry to estimate the true hemoglobin oxygen saturation of arterial blood. Oxyhemoglobin (HbO₂) absorbs visible and infrared light differently than deoxyhemoglobin (Hb) and appears bright red as opposed to the darker brown of Hb. Absorption in the arterial blood is represented by an AC signal that is superimposed on a DC signal, representing absorptions in other substances like pigmentation in tissue, venous, capillary, bone, and so forth. The cardiac-synchronized AC signal is approximately 1% of the DC level. This value is referred to as the perfusion index percentage. [Equation 1](#) approximates the ratio of ratios, R, and percent SpO₂ as follows:

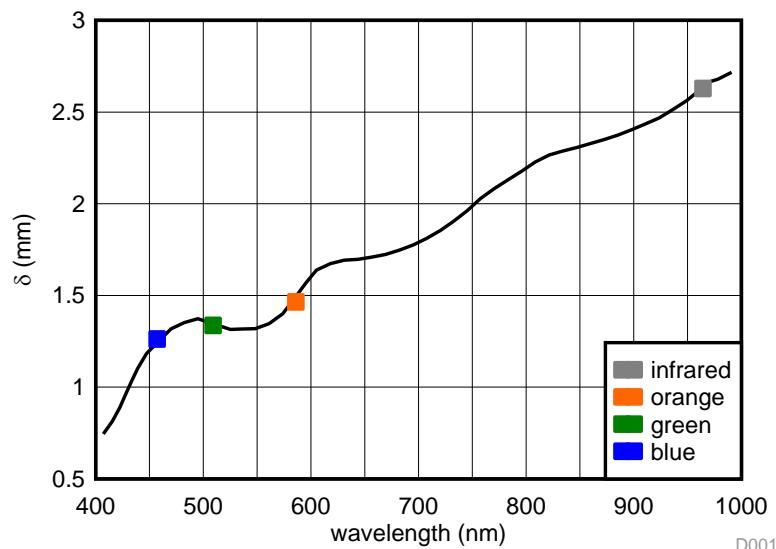
$$R = \frac{\text{ACrms of Red}}{\text{DC of Red}} / \frac{\text{ACrms of IR}}{\text{DC of IR}} \quad (1)$$

[Equation 2](#) gives the standard model of computing SpO₂. This model is often used in this literature in the context of medical devices. However, accurate percentage of SpO₂ is computed based on the empirical calibration of the ratio of ratios for the specific device.

$$\%SpO_2 = 110 - (25 \times R) \quad (2)$$

The reliability of PPG signals measured during normal daily life can be reduced by motion artifacts. Thus, various techniques for the robust measurement of PPG signals during motion have been researched. One approach, based on the optical characteristics of tissue, can be the choice of light wavelength. The light sources used with PPG have been chosen at various wavelengths including the near-infrared (NIR) (for example, 810 or 940 nm), red, green, and blue. NIR and red wavelengths are generally used in PPG research and for routine clinical applications. However, among the possible light colors, green light PPG has been shown to have the least influence from motion artifacts when compared with the NIR light PPG. In fact, green light PPG is now often used in smartphone heart rate (HR) measurement, which is available not only in the laboratory but also during normal daily life. Naturally, the influences of artifacts on the PPG signal are related to the wavelength of the light source simply because of the wavelength dependence of the light absorption (for example, water, melanin, oxy- and deoxyhemoglobin) and therefore the penetration depth into the tissue. The additional wavelengths can also be used to distinguish the absorption of deoxyhemoglobin (RHb) and oxyhemoglobin (HbO₂). More details are available in [Section 6](#) (Reference 6) and [Figure 1](#).

Figure 1. Optical Penetration Depth δ Shown for a Range of Light Sources of Different Wavelengths



1.2 Typical Applications

- **Wireless Patient Monitor:** Wireless patient monitors measure vital signs and send data across to a remote location through wireless technology (Bluetooth®, Bluetooth® low energy, Wi-Fi®, Sub 1-GHz or NFC/RFID). These monitors are typically battery-powered and have low operating currents to work for longer battery life. The solutions are notably compact, unlike multiparameter bedside monitors.
- **Medical Sensor Patches:** Medical sensor patches are wearable, battery-operated patient monitors which can be stuck on the human body for measurement of different parameters like ECG, temperature, blood pressure, and so forth.
- **Pulse Oximeter:** The pulse oximeter measures blood oxygenation by sensing the IR and red-light absorption properties of deoxygenated and oxygenated hemoglobin. The oximeter is comprised of a sensing probe that attaches to the ear lobe, toe, or finger of a patient and is connected to a data acquisition system for calculation and display of the oxygen saturation level, heart rate, and blood flow. Light sources, typically LEDs, shine visible red and IR light. Deoxygenated hemoglobin allows more infrared light to pass through and absorb more red light. Highly oxygenated hemoglobin allows more red light to pass through and absorbs more IR light. The oximeter senses and calculates the amount of light at those wavelengths proportional to the oxygen saturation (or desaturation) of the hemoglobin. The use of light in the absorbency measurement requires the designer to have a true light-to-voltage conversion using current as the input signal.
- **Wearable Fitness and Activity Monitor:** Fitness monitors measure both the amount and rate of exercise of a person (for example, miles and pace run) as well as effort expended (for example, through monitoring heart rate). Typically, a wristwatch or wrist-worn display is used for control and providing feedback. Stored data can be downloaded to a computer through a USB or wireless USB dongle. All parts of the system require ultra-low power, embedded controllers and low-power RF for communication. Heart-rate monitoring and exercise-output monitoring (for example, a running pace sensor or power sensor) require additional signal conditioning.
- **Multiparameter Patient Monitor:** Multiparameter patient monitors measure vital signs and send across to a remote location through wired or wireless technology (Bluetooth®, Bluetooth® low energy, Wi-Fi®, Sub 1-GHz or NFC/RFID) or to a local storage. These monitors have different modules to measure different vital signs.
- Other adjacent applications which can use multi-wavelength optical measurement are food analyzers, air particle analyzers, and air purifiers.

1.3 System Specifications and Design Features

The TIDA-010029 reference design is a wearable patient monitor and has the following features:

- Simple, wearable, PPG measurement design that provides raw data to calculate heart rate, SpO₂, and other related parameters
- Single-chip, bio-sensing, front end for high-resolution PPG measurements (AFE4420 device)
 - Only device on the market with this level of integration, low power, size, and flexibility
 - Supports 4 LEDs and 4 PDs with digital ambient subtraction to improve the signal-to-noise ratio (SNR)
 - Flexibility of ultra-low-power modes and integrated FIFO can keep the MCU in sleep mode to increase the battery operation time
 - Signal acquisition of up to 16 phases and flexible allocation of LEDs and PDs in each phase enable multi-wavelength measurements
- Wireless data transfer supporting Bluetooth low energy 4.2 and 5.0
 - Integrated Arm Cortex-M3 and 2.4-GHz RF transceiver (CC2640R2F device)
 - Internal DC/DC converter helps improve the overall efficiency
 - Built-in, low-battery detection algorithm helps reduce the external components
 - Better routing in small form factor (all digital peripheral pins can be routed to any general-purpose input/output (GPIO))
- Operated from CR3032 (3-V, 500-mA coin-cell battery), which offers 100 hours of continuous operation
- Low-power (battery life of 30 days for 1 second/minute transmission)
- Can also be operated using CR2032 (3-V, 225-mA coin cell battery) with reduced operating time
- Plug-in board approach enables easy adaptation to custom PPG sensors

1.4 Key System Specifications

Table 1 lists the different characteristics and specifications of the TIDA-010029 board.

Table 1. Key System Specifications and Capabilities

CHARACTERISTICS	SPECIFICATIONS
Input voltage (V_{IN})	1.8 V to 3 V (coin-cell CR3032 battery)
TX_SUP	4.2 V
RX_SUP	2.1 V
IO_SUP	2.1 V
Number of LEDs for PPG measurement	Three (green, red, and IR)
Number of photodiodes for PPG measurement	Two (for SFH7072)
External memory	Supported, but not populated onboard
LED indications	Low-battery flag
	Bluetooth low energy (BLE) status
Communication	SPI
Interface to controller	8-pin connector (100 mil, part number PRPC008SADN-RC)
Board dimension (main board)	75 mm x 50 mm
Board dimension (sensor board)	28 mm x 28 mm

2 System Overview

2.1 Block Diagram

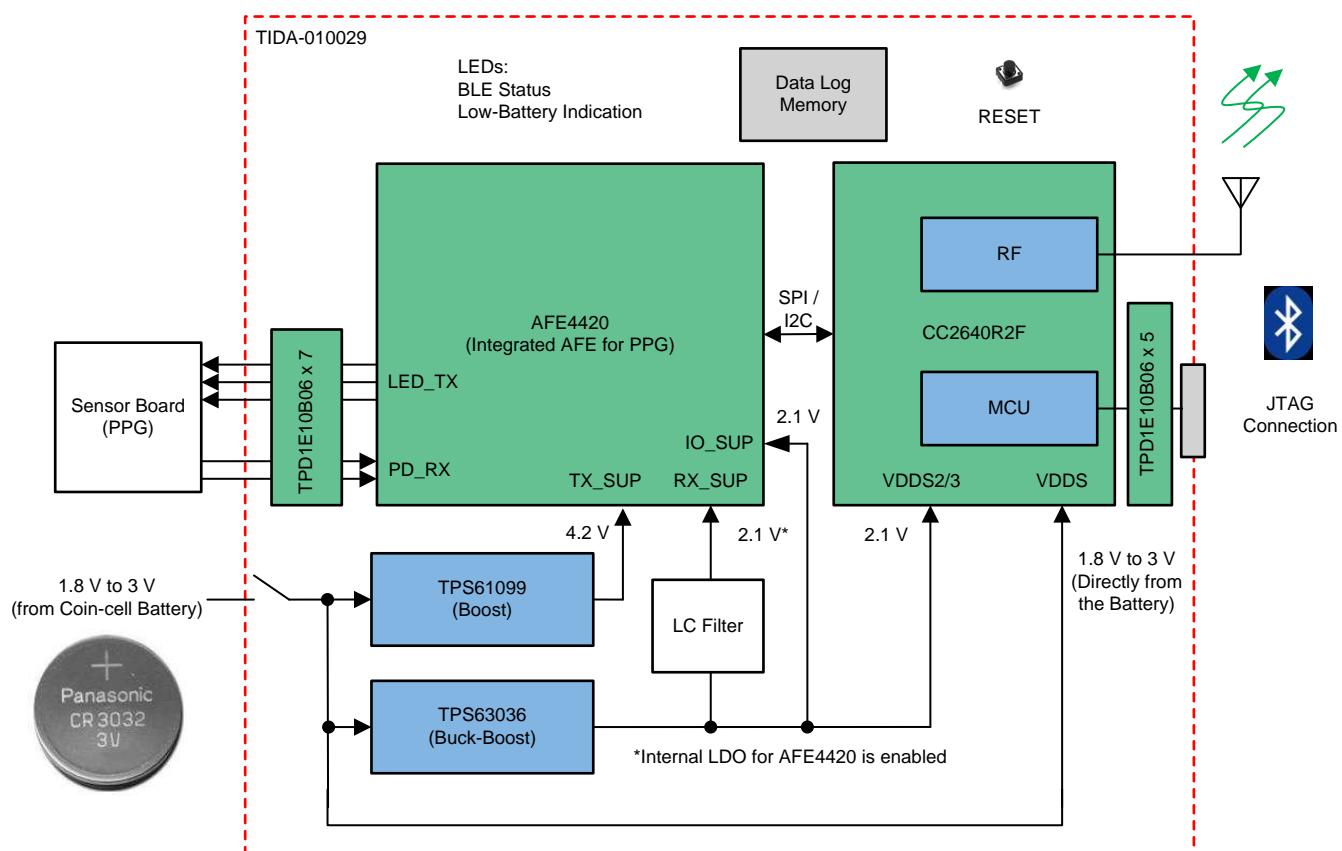
Figure 2 shows the high-level block diagram for the TIDA-010029 device, which is a simple, wearable, optical heart-rate and SpO₂ monitor. The AFE4420 is a single-chip, bio-sensing, front end for PPG measurements. The AFE4420 device can drive up to 4 LEDs and support receive signal chains for up to 4 photodiodes. The flexible allocation of LEDs and PDs in each phase can enable multi-wavelength measurements. The AFE4420 device communicates with the CC2640R2F device over serial peripheral interface (SPI), or I²C. The CC2640R2F is a microcontroller with an integrated Arm® Cortex®-M3 and 2.4-GHz RF transceiver. The design supports wired data capture using a JTAG connection, as well as wireless data capture by sending it over Bluetooth® low energy (BLE) through the antenna.

The board is powered using a 3-V, 500-mA coin-cell battery, CR3032. A boost converter (TPS61099) powers TX_SUP for the AFE4420 device, which supports the internal LED drivers for PPG measurement. A buck-boost converter (TPS63036) powers RX_SUP and IO_SUP for the AFE4420 device and VDDS2 and VDDS3 for the CC2640R2F device. VDDS for the CC2640R2F device is directly powered by the battery.

The board supports connections to external data-log memory, but it is currently not populated. The board indicates battery power source availability, low-battery detection, Bluetooth low energy connection status, and lead-off detection through onboard LEDs.

All the connections from the main to the external world are protected by electrostatic discharge (ESD) diodes (TPD1E10B06). The design contains a main board and a sensor board.

Figure 2. TIDA-010029 Block Diagram



2.2 Highlighted Products

Key features of the highlighted devices are mentioned in the following sections.

2.2.1 AFE4420

The AFE4420 device is an analog front-end (AFE) for PPG signal acquisition. The device can also be used for optical bio-sensing applications, such as heart-rate monitoring (HRM) and SpO₂. The PPG signal chain supports up to 4 switching LEDs and up to 4 PDs. The LEDs can be switched on using a fully-integrated LED driver. The current from the PD is converted into voltage by the trans-impedance amplifier (TIA) and digitized using an analog-to-digital converter (ADC). The ADC codes from the PPG phases can be stored in a 128-sample first in, first out (FIFO) block and read out using either an I²C or SPI.

2.2.2 CC2640R2F

The CC2640R2F device is a wireless MCU targeting Bluetooth® low energy 4.2 and 5 applications. The device is a member of the SimpleLink™ ultra-low-power CC26xx family of cost-effective, 2.4-GHz RF devices. Low active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin-cell batteries and in energy-harvesting applications. The SimpleLink Bluetooth low energy CC2640R2F device contains a 32-bit Arm Cortex-M3 core, which runs at 48 MHz as the main processor and a rich peripheral feature set, which includes a unique ultra-low power sensor controller. This sensor controller is ideal for interfacing external sensors and for collecting analog and digital data autonomously while the rest of the system is in sleep mode. Thus, the CC2640R2F device is great for a wide range of applications where long battery lifetime, small form factor, and ease of use are important. The power and clock management and radio systems of the CC2640R2F wireless MCU require specific configuration and handling by software, which has been implemented in the TI-RTOS, to operate correctly.

2.2.3 TPS61099

The TPS61099 boost converter uses a hysteretic control topology to obtain maximum efficiency at minimal quiescent current. The TPS61099 device only consumes 1- μ A quiescent current under a light load condition and can achieve up to 75% efficiency at a 10- μ A load with a fixed output voltage version. The TPS61099 device can also support up to 300-mA output current from 3.3 V to 5 V conversion and achieve up to 93% at a 200-mA load. The TPS61099 device also offers both Down Mode and Pass-Through operations for different applications. In Down Mode, the output voltage can still be regulated at a target value even when the input voltage is higher than the output voltage. In Pass-Through Mode, the output voltage follows the input voltage. The TPS61099x device exits Down Mode and enters into Pass-Through Mode when $V_{IN} > V_{OUT} + 0.3$ V. The TPS61099x device supports true shutdown function when it is disabled, which disconnects the load from the input supply to reduce the current consumption. The TPS61099x device offers both an adjustable output voltage version and fixed output voltage version. The TPS61099x device is available in a 6-ball, 1.23-mm × 0.88-mm, W CSP package.

2.2.4 TPS63036

The TPS63036 is a noninverting, buck-boost converter capable of providing a regulated output voltage from an input supply that can be higher or lower than the output voltage. The buck-boost converter is based on a fixed-frequency, pulse width modulation (PWM) controller, which uses synchronous rectification to obtain maximum efficiency. At low-load currents, the converter enters a power-save mode to maintain high efficiency over a wide-load current range. The power save mode can be disabled, forcing the converter to operate at a fixed switching frequency. The maximum average current in the switches is limited to a typical value of 1000 mA. The output voltage is programmable using an external resistor divider. The converter can be disabled to minimize battery drain.

2.2.5 TPD1E10B06

The TPD1E10B06 device is a single-channel, electrostatic discharge (ESD), transient voltage suppression (TVS) diode in a small 0402 package. This TVS protection product offers ±30-kV contact ESD, ±30-kV IEC air-gap protection, and an ESD clamp circuit, with a back-to-back TVS diode for bipolar or bidirectional signal support. The 0402 package is an industry standard and is convenient for component placement in space-saving applications.

NOTE: The CC2642R device is a new and small wireless MCU device targeting Bluetooth® 4 and 5 low energy applications. The CC2642R1FRGZ device is pin-compatible with the CC2640R2FRGZR device.

2.3 System Design Theory and Design Considerations

This section explains the design theory for each of the devices used in the design.

2.3.1 AFE4420 and Power Supply

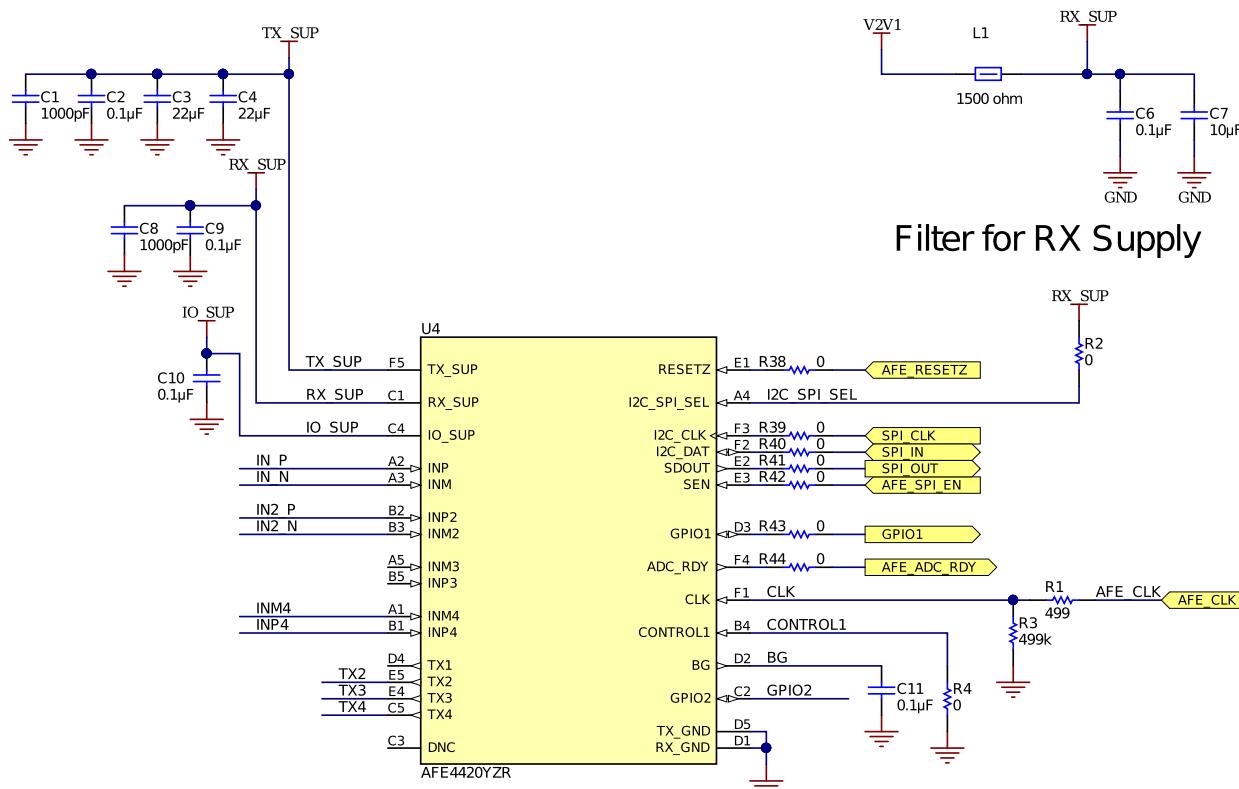
Figure 3 shows different connections for the AFE4420 device.

The AFE4420 device needs three power supplies: TX_SUP, RX_SUP, and IO_SUP. TX_SUP (4.2 V) is generated using the TPS61099 device. RX_SUP (2.1 V) is generated using the TPS63036 device. IO_SUP is the same as RX_SUP.

For PPG measurement, the LEDs are driven using the TX2, TX3, and TX4 pins (TX1 is not connected in the design). The reflected signals are detected using PDs connected to the INP-INM and INP2-INM2 pins (INP3-INM3 and INP4-INM4 pins are not connected in the design).

The BG pin is connected to the internal bandgap voltage. The BG pin is decoupled using a 0.1- μ F capacitor (C11) on the board.

Figure 3. AFE4420 Connections Schematic



For the AFE4420 device, RX_SUP is filtered using an LC filter consisting of the ferrite bead L1 and capacitors C6 and C7.

Table 2 lists the connections between the AFE4420 and CC2640R2F devices.

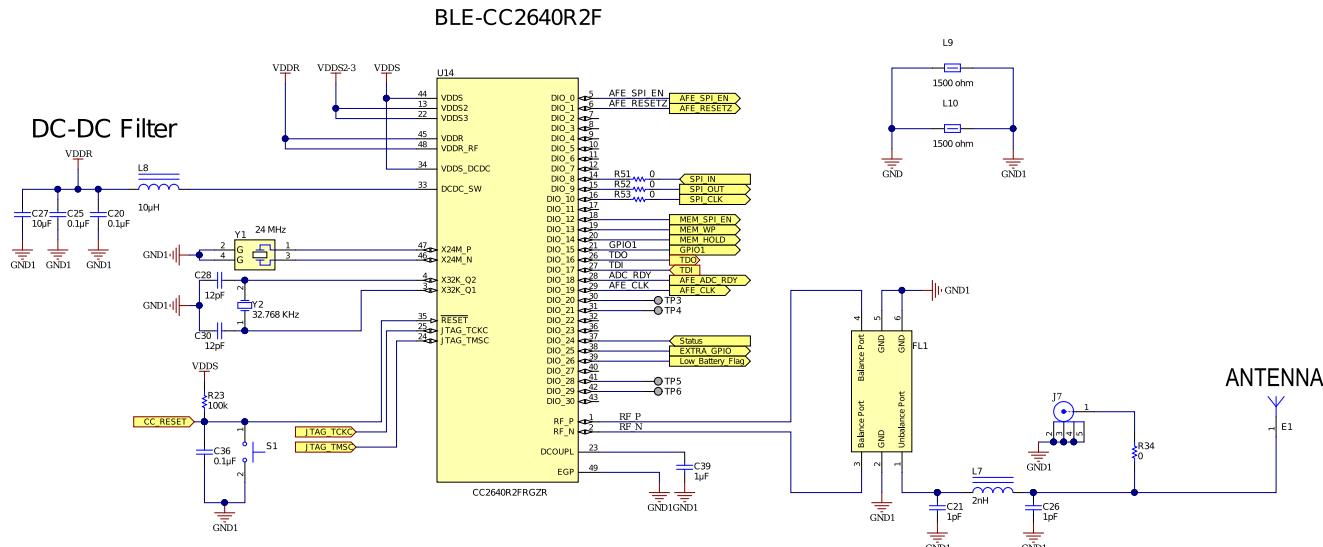
Table 2. Connections Between AFE4420 and CC2640R2F

AFE4420 PIN NUMBER	FUNCTION	CC2640R2F PIN NUMBER	FUNCTION	COMMENTS
E1	/RESET	6	DIO_1	Reset for the AFE
A4	I2C_SPI_SEL	N/A	N/A	Selection between SPI and I ² C. For this design, SPI is selected, so this pin is connected to RX_SUP through a 0-Ω resistor (R2).
F3	I2C_CLK	16	DIO_10	SPI_CLK
F2	I2C_DAT	14	DIO_8	SPI_IN
E2	SDOUT	15	DIO_9	SPI_OUT
E3	SEN	5	DIO_0	AFE_SPI_EN
D3	GPIO1	21	DIO_15	Extra GPIO
F4	ADC_RDY	28	DIO_18	ADC ready signal
F1	CLK	29	DIO_19	AFE clock
B4	CONTROL1	N/A	N/A	Enables or disables the internal LDO. For this design, the internal LDO is enabled, so this pin is connected to GND through a 0-Ω resistor (R4).

2.3.2 CC2640R2F Microcontroller

Figure 4 shows the schematic for configuring the CC2640R2F MCU.

Figure 4. CC2640R2F MCU Schematic

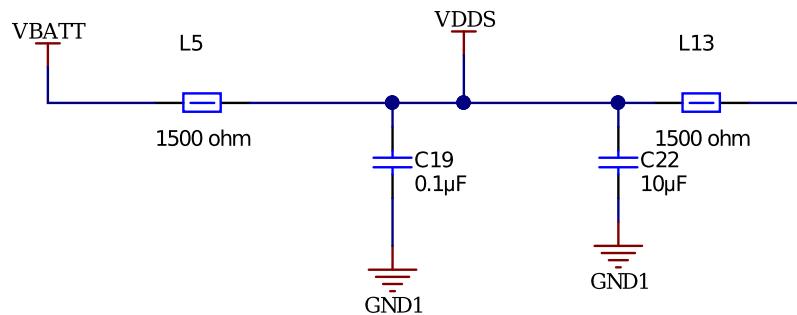


The VDSS power supply for the MCU, 2.1 V, is derived using the TPS63036 device. The VDDR power supply is generated using the internal DC/DC of the CC2640R2F MCU, and L8, C20, C25, and C27 form the filter components for the same. Y1 is the 24-MHz, high-frequency external clock, and Y2 is the 32-kHz, low-frequency external clock. The GPIO pins of the CC2640R2F MCU (DIO_0 to DIO_30) interface with different functions such as memory interface lines, AFE4420 interface lines, SPI communication, LED drives, and so forth.

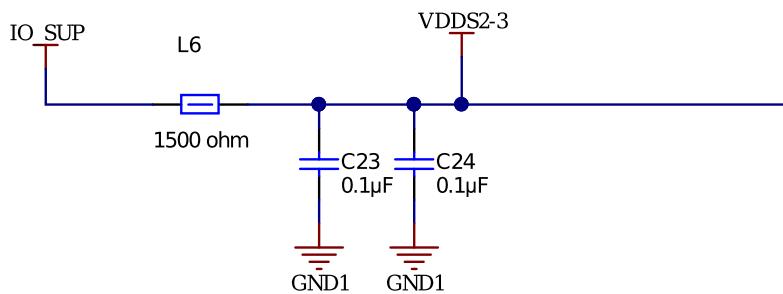
The RF front end is used in differential-ended configurations with internal biasing. A balun LFB182G45BG5D920 device is used for the RF front end and tuned for application. J7 is a connector for conducted RF measurements, if required. The antenna is a PCB antenna.

Figure 5. Decoupling for CC2640R2F MCU

VDDS Decoupling Capacitors

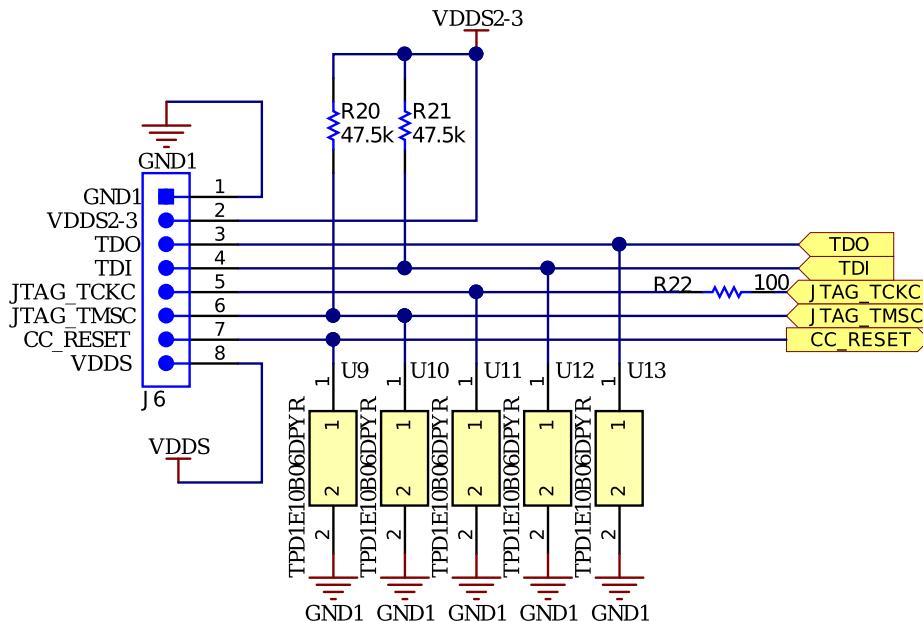


VDDS2-3 Decoupling Capacitors



VBATT is connected to VDSS through L5, a GHz noise-suppression chip ferrite bead, providing a low-noise supply to the MCU. C19 and C22 are the decoupling capacitors. A 2.1 V is connected to the VDDS2 and VDDS3 pins through L6, a GHz noise-suppression chip ferrite bead, providing a low-noise supply to the MCU. C23 and C24 are the decoupling capacitors, as shown in [Figure 5](#).

Figure 6. MCU Programming Connector



The MCU is programmed using a JTAG connection, as shown in Figure 6. The connector inputs are protected by ESD diodes (TPD1E10B06DPYR) from Texas Instruments. The TPD1E10B06 device is a single-channel, ESD, TVS diode in a small 0402 package. This TVS protection product offers $\pm 30\text{-kV}$ contact ESD, $\pm 30\text{-kV}$ IEC air-gap protection, and an ESD clamp circuit with a back-to-back TVS diode for bipolar or bidirectional signal support.

2.3.3 PPG Measurement

For PPG measurement, three LEDs and two PDs are used in a single package. Table 3 lists details about the SFH7072 from OSRAM®.

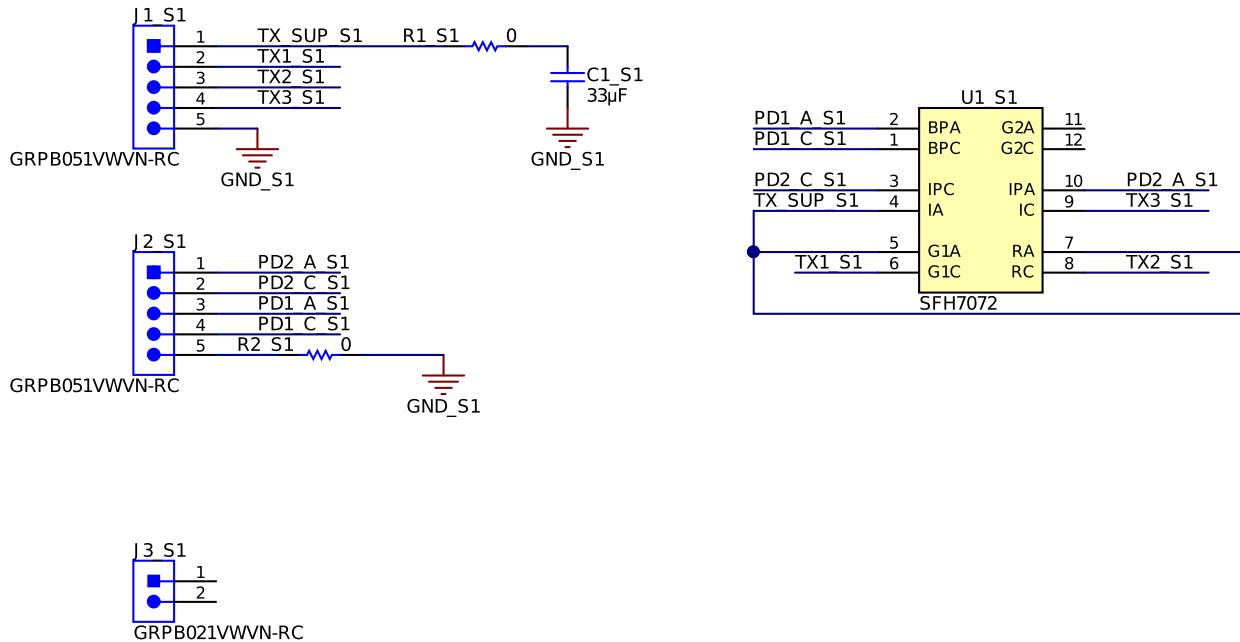
Table 3. Optical Sensors

SENSOR	SFH7072
Number of LEDs	4
Number of PDs	2
LED1 color	Green
LED1 wavelength	526 nm
LED2 color	Green
LED2 wavelength	526 nm
LED3 color	Red
LED3 wavelength	660 nm
LED4 color	IR
LED3 wavelength	950 nm
LED1 VF (typ)	1.3
LED1 VF (max)	1.8
LED2 VF (typ)	2.1
LED2 VF (max)	2.8
LED3 VF (typ)	3
LED3 VF (max)	3.4
LED4 VF (typ)	3

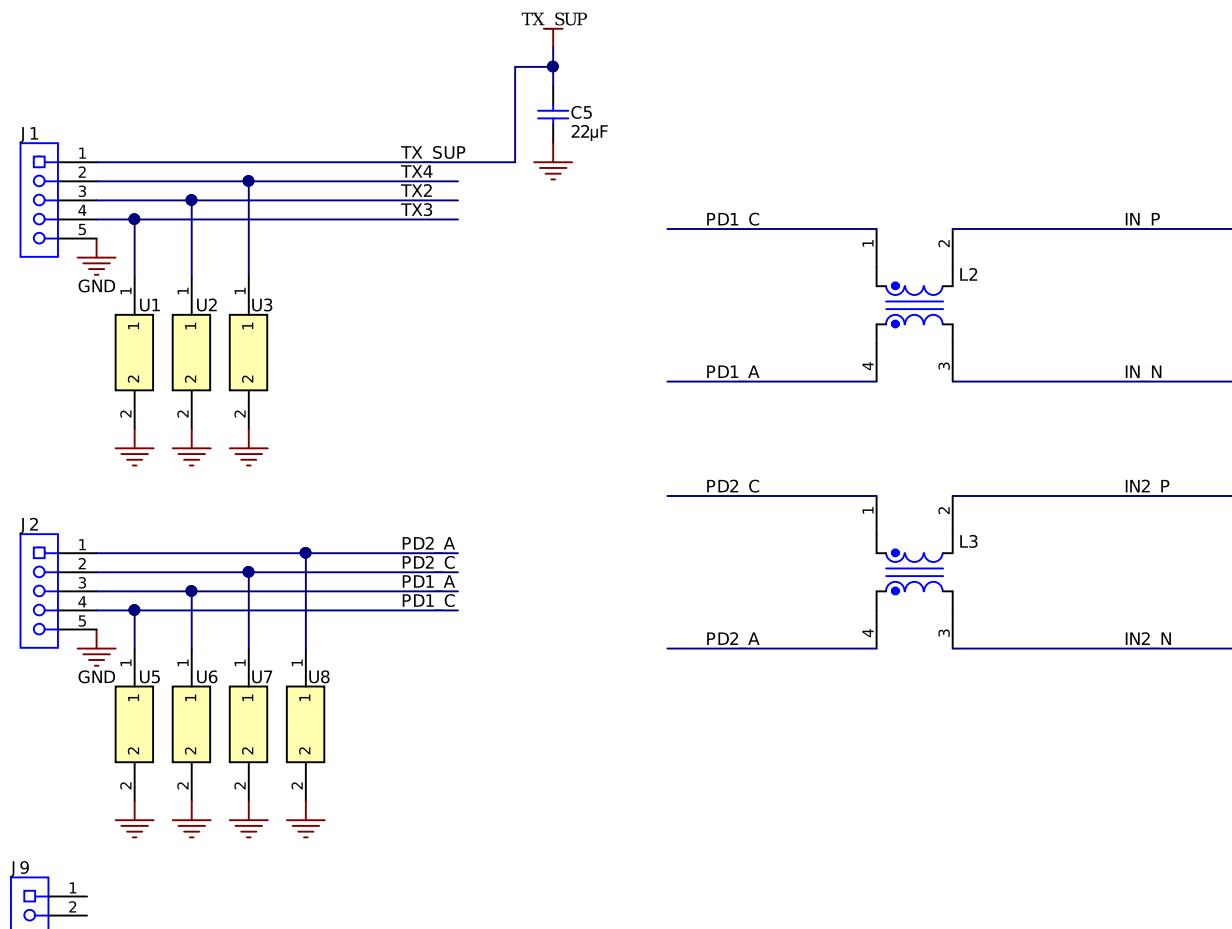
Table 3. Optical Sensors (continued)

SENSOR	SFH7072
LED4 VF (max)	3.4

The sensor boards are designed to fit on the main board with 5-pin connectors based on the LEDs and PDs available in the optical sensor. All of the LEDs are configured in push-pull, or common anode mode. See [Figure 7](#) for the connection diagrams.

Figure 7. Sensor Board Schematic With SFH7072 Device

The sensor boards are fit onto the main board using the J1 and J2 connector, as shown in [Figure 8](#).

Figure 8. PPG Connection From Sensor Board to AFE4420 Device on Main Board


The J1 connector has 5 connections: TX_SUP, TX drive pins, and GND. The J2 connector has 5 connections: PD1 Anode and Cathode, PD2 Anode and Cathode, and GND. The connector inputs are protected using ESD diodes (TPD1E10B06DPYR) from Texas Instruments. The TPD1E10B06 device is a single-channel, ESD, TVS diode in a small 0402 package. This TVS protection product offers $\pm 30\text{-kV}$ contact ESD, $\pm 30\text{-kV}$ IEC air-gap protection, and an ESD clamp circuit with a back-to-back TVS diode for bipolar or bidirectional signal support. The TX_SUP pin is decoupled using a $33\text{-}\mu\text{F}$ capacitor.

The PD signals are filtered using SMD Common Mode Chokes (having specifications as $90\ \Omega$ at 100 MHz, $370\text{-mA DCR } 300\text{ m}\Omega$). The chokes help in improving the immunity to external common mode noise signals and improve overall SNR of the system.

2.3.4 Selecting TX Supply (TX_SUP) Value for Driving LEDs

Table 4 shows the recommended TX_SUPPLY voltage range, taken from the AFE4420 device data sheet.

Table 4. Recommended TX_SUPPLY Value

		MINIMUM	NOM	MAXIMUM	UNIT
RX_SUPPLY	Receiver supply: LDO Bypass mode	1.7		1.9	V
	Receiver supply: LDO Enabled mode	1.9		Min (3.6, TX_SUPPLY)	V
IO_SUPPLY	I/O supply	1.7		RX_SUPPLY	V
TX_SUPPLY	Transmitter supply	3		5.5	V
	Digital inputs (Except CONTROL1, I2C_SPI_SEL)	0		IO_SUPPLY	V

Table 4. Recommended TX_SUP Value (continued)

		MINIMUM	NOM	MAXIMUM	UNIT
	Analog inputs (And CONTROL1, I2C_SPI_SEL)	0		RX_SUP	V
T _A	Operating temperature range	-40		85	°C

Table 5 shows the headroom voltage, V_{HR}.

Table 5. Headroom Voltages

ILED_FS REGISTER	TEX_REF VOLTAGE	1 LED DRIVER ON		2 LED DRIVERS ON THROUGH SAME LED		2 LED DRIVERS ON THROUGH 2 LEDs	
		MAXIMUM CURRENT	V _{HR}	MAXIMUM CURRENT	V _{HR}	MAXIMUM CURRENT	V _{HR}
00	150 mV	50 mA	320 mV	100 mA	370 mV	50 mA	345 mV
01	300 mV	100 mA	600 mV	200 mA	650 mV	100 mA	625 mV
11	375 mV	100 mA	700 mV	200 mA	750 mV	100 mA	725 mV

$$TX_{SUP} = V_{LED} + V_{HR} + 0.3 = 3.2 + 0.625 + 0.3 = 4.125 \text{ V} \quad (3)$$

Select TX_{SUP} = 4.2 V.

2.3.5 Generating TX Supply for Driving LEDs

Table 6. Specifications for TX_SUP

PARAMETER	VALUE
Input voltage	1.8 V to 3.0 V
Output voltage	4.2 V
Output current	50 mA
Output voltage ripple	±50 mV

2.3.5.1 Programming Output Voltage

The output voltage is programmed to 4.2 V using [Equation 4](#), where V_{REF} = 1.0 V. For best accuracy, the current following through R36 should be 100 times larger than the FB pin leakage current.

$$V_{OUT} = V_{REF} \times \frac{R35 + R36}{R36} \quad (4)$$

Because V_{OUT} = 4.2 V and R36 = 100 kΩ, R35 = 320 kΩ. TI recommends high-accuracy resistors for better output voltage accuracy. The TIDA-010029 device uses both resistors with 0.5% tolerance.

2.3.5.2 Maximum Output Current

The maximum output capability of the TPS61099 device is determined by the input-to-output ratio and the current limit of the boost converter.

[Equation 5](#) shows I_{OUT(max)} = 300 mA (V_{IN} = 1.8 V, I_{LIM} = 1 A, I_{LH} = 350 mA, η = 85%, and V_{OUT} = 4.2 V).

$$I_{OUT(max)} = \frac{V_{IN} \times \left(I_{LIM} - \frac{I_{LH}}{2} \right) \times \eta}{V_{OUT}} \quad (5)$$

2.3.5.3 Input and Output Capacitor Selection

For the best output and input voltage filtering, TI recommends low-ESR X5R or X7R ceramic capacitors. The input capacitor minimizes input voltage ripple, suppresses input voltage spikes, and provides a stable system rail for the device. An input capacitor value of 10 μF (C47) is used to improve transient behavior of the regulator and EMI behavior of the total power supply circuit. TI recommends placing a ceramic capacitor as close as possible to the VIN and GND pins of the IC.

For the output capacitor of the VOUT pin, ceramic capacitors (C49 and C53) are placed as close as possible to the VOUT and GND pins of the IC. This capacitor must be placed as close as possible to the VOUT and GND pins of the IC. From the power-stage point of view, the output capacitor sets the corner frequency of the converter, while the inductor creates a Right-Half-Plane-Zero. Consequently, with a larger inductor, a larger output capacitor must be used. The TPS61099x device is optimized to work with the inductor from 1 μH to 2.2 μH , so the minimal output capacitor value is 20 μF (nominal value). Increasing the output capacitor makes the output ripple smaller in PWM mode.

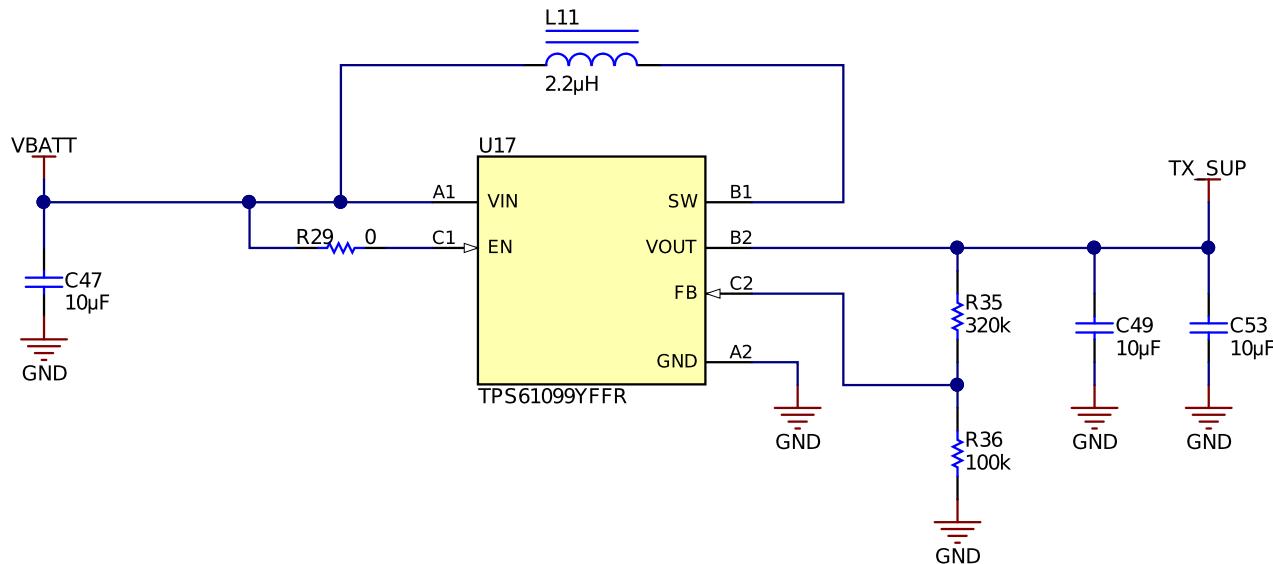
2.3.5.4 Switching Frequency

The switching frequency is calculated as [Equation 6](#).

$$f = \frac{V_{\text{IN}} \times (V_{\text{OUT}} - V_{\text{IN}} \times \eta)}{L \times I_{\text{LH}} \times V_{\text{OUT}}} = \frac{1.8 \times (4.2 - 1.8 \times 0.85)}{2.2 \mu\text{H} \times 0.35 \times 4.2} = 1.48 \text{ MHz} \quad (6)$$

[Figure 9](#) shows the schematic for the boost converter, TPS61099.

Figure 9. TPS61099 Boost Converter ($V_{\text{OUT}} = 4.2 \text{ V}$)



2.3.5.5 WEBENCH® Simulation for TPS61099 Boost Converter

Figure 10 and Figure 11 show the WEBENCH® simulation for the TPS61099 boost converter. For any custom requirement, simulation is available on the [TPS61099 product page](#).

Figure 10. WEBENCH® Simulation for TPS61099 Boost Converter (Schematic)

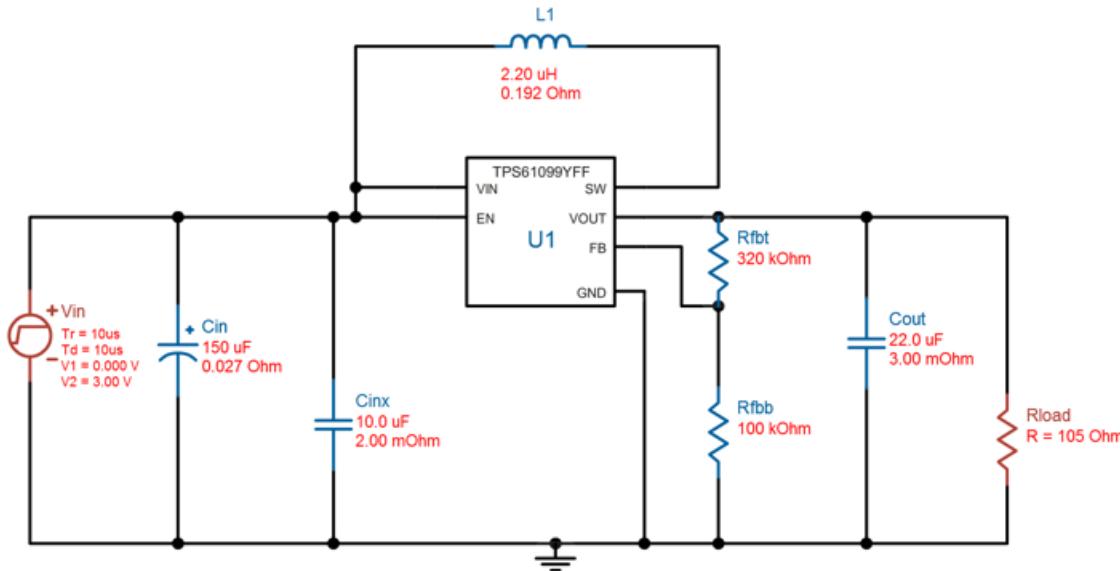
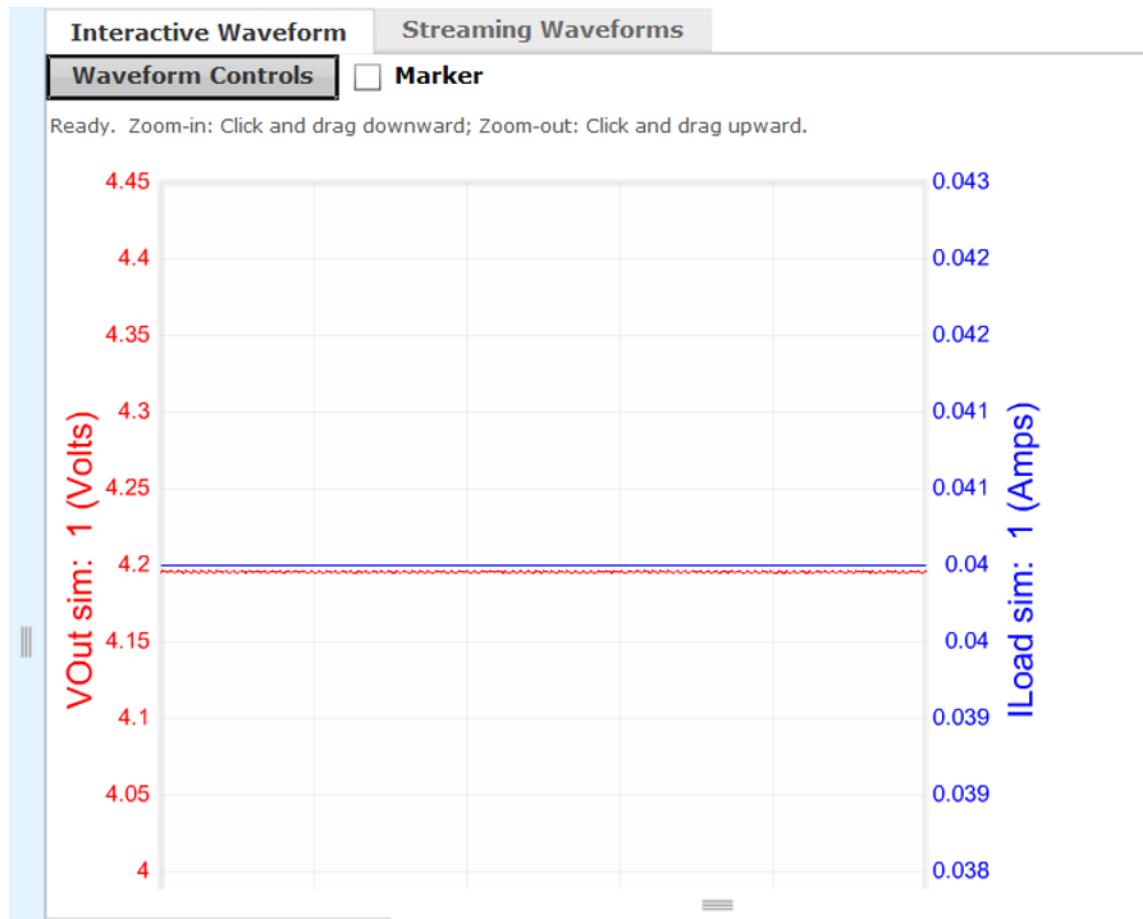


Figure 11. WEBENCH® Simulation for TPS61099 Boost Converter (Test Results)



2.3.6 Generating RX Supply for AFE4420

Table 7. Specifications for RX_SUP

PARAMETER	VALUE
Input voltage	1.8 V to 3.0 V
Output voltage	2.1 V
Output current	10 mA
Output voltage ripple	±50 mV

2.3.6.1 Setting Output Voltage

The output voltage of the TPS63036 device is set by an external resistor divider connected between VOUT, FB, and GND. When the output voltage is regulated, the typical value of the voltage at the FB pin is 500 mV. The typical current into the FB pin is 0.01 μ A, and the voltage across the resistor between FB and GND, R32, is typically 500 mV. Based on these two values, the recommended value for R32 must be lower than 100 k Ω to set the divider current at 5 μ A or higher (selected value of R32 = 51.1 k Ω). From here, the value of the resistor connected between VOUT and FB, R31, (depending on the needed VOUT), can be calculated using [Equation 7](#).

$$R31 = R32 \times \left(\frac{V_{OUT}}{V_{FB}} - 1 \right) = 51.1k \times \left(\frac{2.1}{0.5} - 1 \right) = 163 \text{ k}\Omega \quad (7)$$

A small capacitor C44 = 10 pF, in parallel with R31, is placed to considerably improve the output voltage ripple.

2.3.6.2 Capacitor Selection

TI recommends at least a 10- μ F input capacitor to improve transient behavior of the regulator and EMI behavior of the total power supply circuit. TI also recommends a ceramic capacitor be placed as close as possible to the VIN and GND pins of the IC (C43 = 10 μ F).

For the output capacitor, TI recommends using small ceramic capacitors placed as close as possible to the VOUT and GND pins of the IC. The recommended typical output capacitor value is 30 μ F. The TIDA-010029 device uses 10 μ F in parallel with 22 μ F. When choosing input and output capacitors, keep in mind that the value of capacitance experiences significant loss from its rated value, depending on the operating temperature and the operating DC voltage. It is not uncommon for a small surface-mount ceramic capacitor to lose 50% and more of its rated capacitance. For this reason, it is important to use a larger value of capacitance or a capacitor with higher voltage rating to ensure the required capacitance at the full operating voltage.

2.3.6.3 Output Current Limit

Table 8. Equations for Boost and Buck Mode in TPS63036

PARAMETER	BOOST MODE	BUCK MODE
Duty cycle	$D = \frac{V_{OUT} - V_{IN}}{V_{OUT}} = \frac{2.1 - 1.8}{2.1} = 0.143$ (8)	$D = \frac{V_{OUT}}{V_{IN}} = \frac{2.1}{3} = 0.7$ (9)
Maximum output current	$I_{OUT} = \eta \times I_{SW} \times (1 - D)$ $I_{OUT} = 0.85 \times 1 \times (1 - 0.143)$ $I_{OUT} = 0.72845 \text{ A}$ (10)	$I_{OUT} = \frac{\eta \times I_{SW}}{D} = \frac{0.85 \times 1}{0.7} = 1.21 \text{ A}$ (11)

2.3.6.4 Inductor Selection

For high efficiency, the inductor must have a low DC resistance to minimize conduction losses. Especially at high-switching frequencies, the core material has a greater impact on efficiency. When using small chip inductors, efficiency is reduced mainly due to higher inductor core losses. This reduction must be considered when selecting the appropriate inductor. The inductor value determines the inductor ripple current. The larger the inductor value, the smaller the inductor ripple current and the lower the conduction loss of the converter. Conversely, larger inductor values cause a slower load-transient response. The peak current for the inductor in steady-state operation can be calculated to avoid saturation of the inductor with the chosen inductance value. The equation which defines the switch current in boost mode is reported because it provides the highest value of current and represents the critical current value for selecting the right inductor.

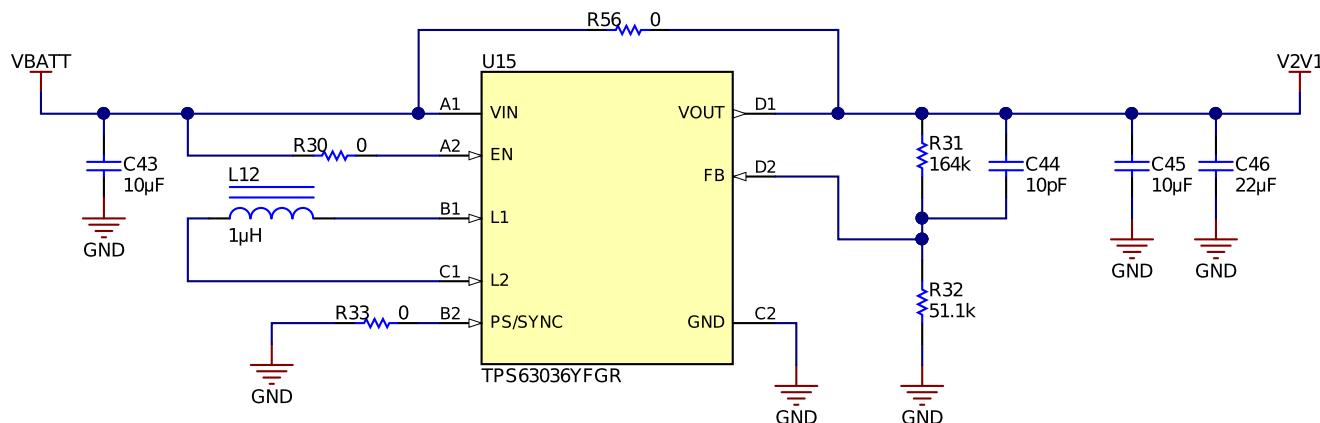
$$I_{PEAK} = I_{SW_MAX} + \frac{V_{IN} \times D}{2 \times f \times L} = 1 + \frac{1.8 \times 0.143}{2 \times 2 \text{ MHz} \times 1 \mu\text{H}} = 1.06435 \text{ A}$$

where,

- D = Duty cycle in boost mode
 - F = converter switching frequency (typical 2 MHz)
 - L = Selected inductor value
 - H = Estimated converter efficiency
 - I_{SW_MAX} = Maximum average input current
- (12)

Figure 12 shows the schematic for the buck-boost converter, TPS63036.

Figure 12. TPS63036 Buck-Boost Converter ($V_{OUT} = 2.1 \text{ V}$)



2.3.6.5 TINA-TI™ Simulation for TPS63036

Figure 13 and Figure 14 show the TINA-TI™ simulation for the TPS63036 buck-boost converter. The TINA simulation file for any custom requirement can be downloaded from the [TPS63036 product page](#).

Figure 13. TINA-TI™ Simulation for TPS61099 Boost Converter (Schematic)

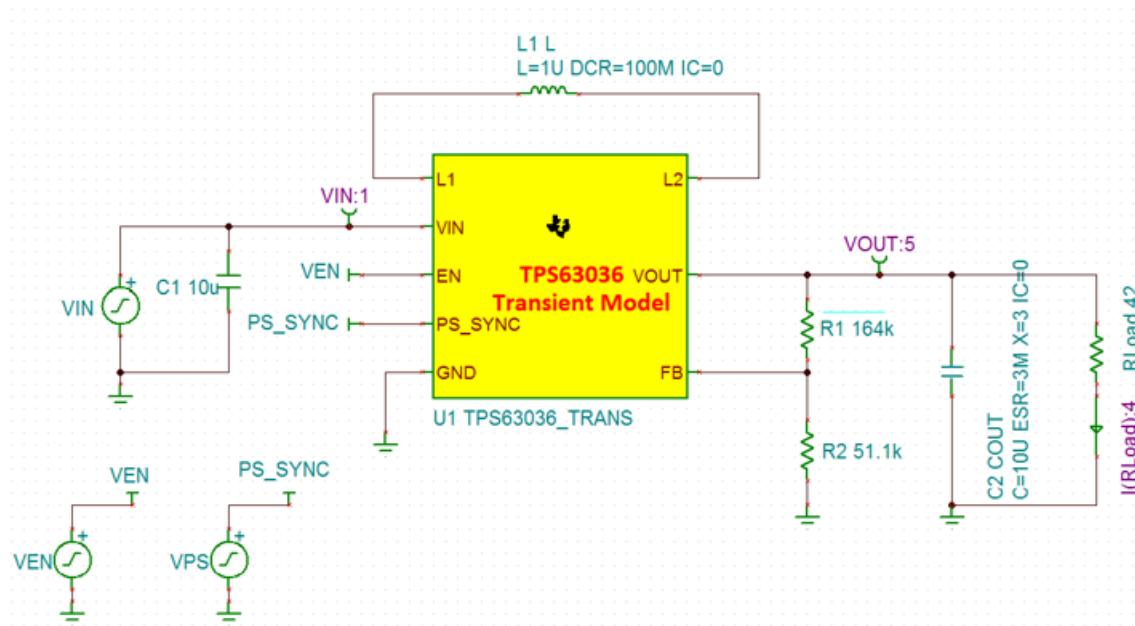
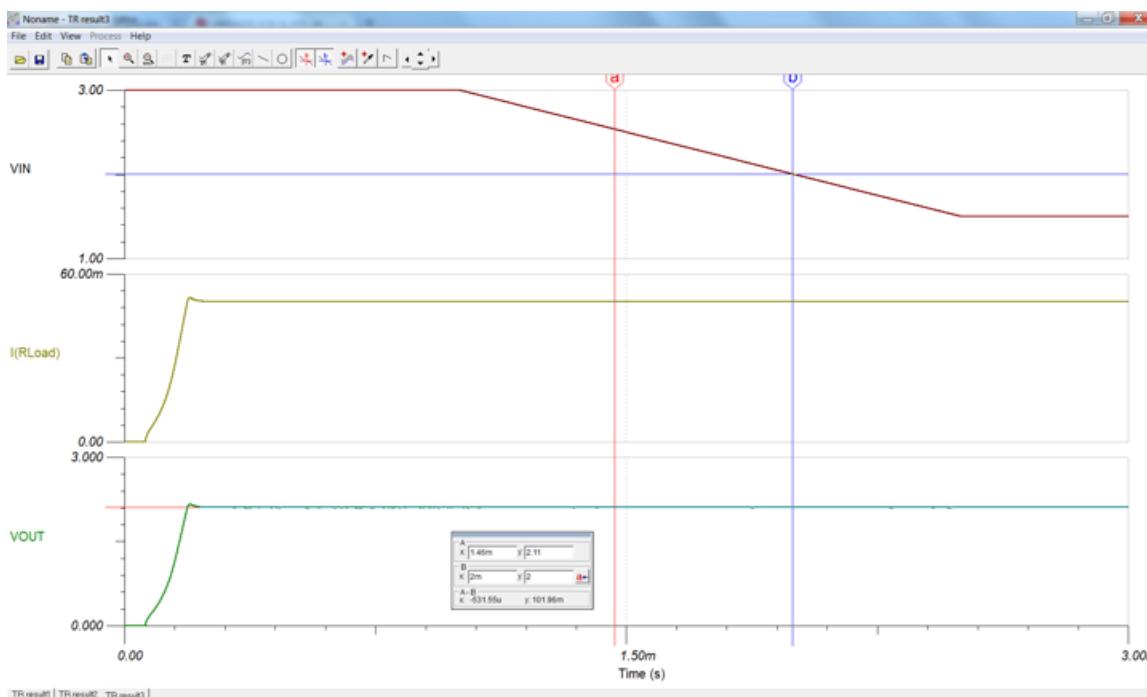


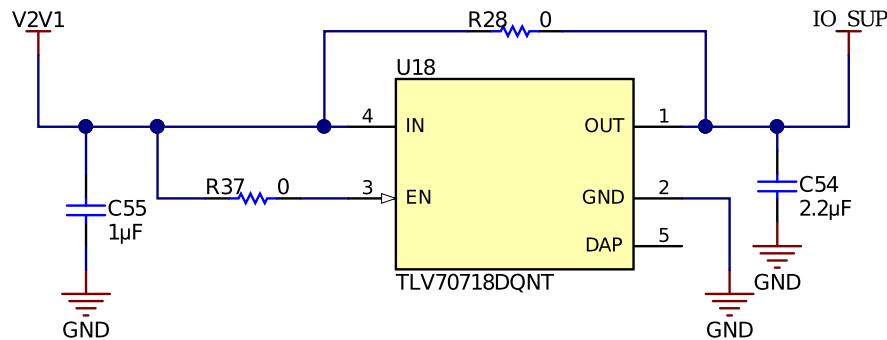
Figure 14. TINA-TI™ Simulation for TPS61099 Boost Converter (Test Results)



2.3.7 Generating I/O Supply

The I/O supply selected is the same as RX-SUP (2.1 V) through R28 ($0\ \Omega$). Another option is to mount an LDO at position U18.

Figure 15. IO_SUP Same as RX_SUP

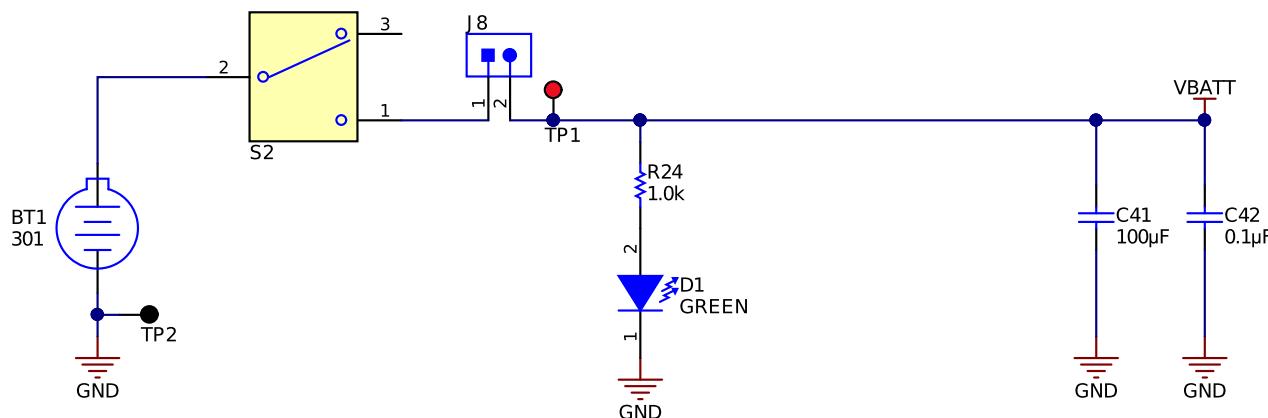


NOTE: U18 is currently not mounted on the TIDA-010029 board. U18 can be mounted if IO_SUP must be different than 2.1 V. LDOs with low drop-out voltages (for example, < 300 mV) have higher quiescent currents which may affect the battery operating time.

2.3.8 Battery Input and Reservoir Capacitors

The power source for this TIDA-010029 device is the CR3032, a lithium-ion coin cell. Selection of the CR2032 coin-cell battery as the power source is due to the ubiquity of the battery type, particularly in small form factor systems. The voltage characteristics of the CR3032 lithium-ion coin cell battery are also ideal. The output voltage remains relatively flat throughout the discharge life until the cell is nearly depleted. When the remaining charge in the coin-cell battery is nearly depleted, the output voltage drops off relatively quickly. The temperature characteristics of lithium-ion batteries are also superior to that of alkaline cells, particularly at lower temperatures. This superiority is due to lithium-ion cells having a non-aqueous electrolyte that performs better than the aqueous electrolytes commonly found in alkaline batteries.

Figure 16. Battery Connector and Reservoir



Given an appropriate weather-proof enclosure, this TI reference design system is suited for both indoor and outdoor use. Immediately following the battery is a bulk capacitor. This TI reference design uses a coin-cell battery tray that prevents an end-user from inserting the battery backwards, which may eliminate the need for the reverse Schottky diode. The bulk capacitor is sized to prevent too much voltage sag, particularly during the initial transition into the on state, as shown in [Figure 16](#).

2.3.9 Battery Life Calculations

This section explains the calculations for battery life of the CR3032 coin-cell battery. The possible current paths in this design are:

- Battery to AFE4420, through the Boost (TPS61099) to the TX_SUP pin
- Battery to AFE4420, through the Buck-Boost (TPS63036) to the RX_SUP/IO_SUP pin
- Battery to CC2640R2F, through the Buck-Boost (TPS63036) to the VDDS2/3 pin
- Battery to CC2640R2F, directly to the VDDS pin

2.3.9.1 AFE4420 Current Consumption

The current consumption of the AFE4420 device depends on the sampling rate (for example, PTT mode at 1-kHz sampling rate for both ECG and PPG).

Typical specifications are at $T_A = 25^\circ\text{C}$; TX_SUP = 5 V, RX_SUP = 1.8 V (with CONTROL1 = 1.8 V to bypass internal LDOs), IO_SUP = 1.8 V, external clock mode with 32-kHz clock on CLK pin (period = $t_{TE} = 31.25 \mu\text{s}$), the AFE operates with ULP mode enabled (ENABLE_ULP = 1); **PPG**: 1-kHz sampling rate, SAMP width of $3 \times t_{TE}$, LED ON width of $4 \times t_{TE}$, C_F chosen such that there are 7-8 TIA time constants within the SAMP width, NUMAV = 1 (2 ADC averages), noise-reduction filter bandwidth set to 2.5 kHz, $C_{IN} = 100 \text{ pF}$ (capacitor across the input pins to model the zero bias differential capacitance of the PD); **ECG**: 1-kHz sampling rate, INA gain of 12, chopper mode enabled (unless otherwise noted).

Table 9. Current Consumption for AFE4420 in Different Modes

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
CURRENT CONSUMPTION					
RX_SUP current excluding switching current from I ² C or SPI readout	Normal operation ⁽¹⁾	21			µA
	Hardware power-down (PWDN) mode ⁽²⁾	<1			
	Software power-down (PDNAFE) mode ⁽²⁾⁽³⁾	1			
RX_SUP current resulting from switching current at I ² C readout	While reading out 100 samples of the FIFO every second. ⁽⁴⁾	3			µA
	Power-down mode	0			
IO_SUP current	Normal operation ⁽¹⁾	1			µA
	Hardware power-down (PWDN) mode ⁽²⁾	<1			
	Software power-down (PDNAFE) mode ⁽²⁾⁽³⁾	1			
TX_SUP current	Normal operation ⁽¹⁾⁽⁵⁾	1.5			µA
	Hardware power-down (PWDN) mode ⁽²⁾⁽⁵⁾	<1			
	Software power-down (PDNAFE) mode ⁽²⁾⁽⁵⁾	1			

⁽¹⁾ Normal operation refers to operation at 25 Hz PRF in external clock mode with a 128 kHz clock, with the device in an active state for 3.5% of the PRF cycle, in Light sleep state for 1% of the PRF cycle and in deep sleep state for 95.5% of the PRF cycle.

⁽²⁾ External clock switched off.

⁽³⁾ In LDO Bypass mode: with PDN_BG_IN_DEEP_SLEEP bit set to 1 along with the PDNAFE bit set to 1. When operation in the LDO Enable mode, the software power-down current on RX_SUP is about 8 µA.

⁽⁴⁾ This current depends on the percentage of time for which the I²C_CLK is low; and scales with PRF and the number of FIFO samples generated in each cycle. This extra component of current is negligible when operating in the SPI interface mode.

⁽⁵⁾ LED currents are set to 0 mA.

Figure 17. RX_SUP Current vs PRF (Excluding FIFO Readout Current)

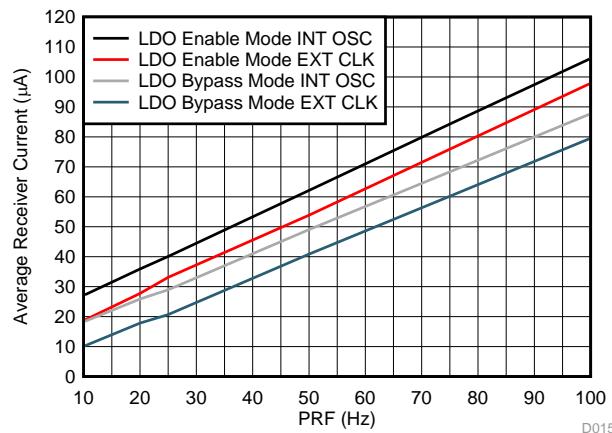
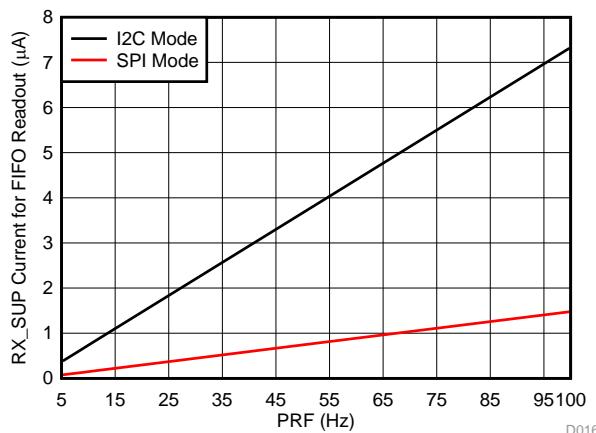


Figure 18. RX_SUP Current for FIFO Readout



The TX_SUP current is taken to be 3 mA at normal operating conditions (10% duty cycle for 100 mA) in the worst case.

Over-operating free-air temperature range unless otherwise noted.

Table 10. LED Drive Currents With Duty Cycles

PARAMETER		MIN	MAX	UNIT
Supply voltage range	RX_SUP to GND; LDO bypassed	-0.3	2.1	V
	RX_SUP to GND; LDO enabled	-0.3	4	
	IO_SUP to GND	-0.3	Min [4, (RX_SUP+0.3)]	
	TX_SUP to GND	-0.3	6	
Voltage applied to analog inputs and to pins CONTROL1, I2C_SPI_SEL		Max [-0.3, (GND - 0.3)]	Min [4.0, (RX_SUP + 0.3)]	V
Voltage applied to digital inputs		Max [-0.3, (GND - 0.3)]	Min [4.0, (IO_SUP + 0.3)]	V
Duty cycle (cumulative): sum of all LED phase durations as a function of the total period	50-mA LED current		10%	
	100-mA LED current		5%	
	200-mA LED current		2.8%	
T _{stg} Storage temperature		-60	150	°C

The RX_SUP and IO_SUP current are taken to be 700 μA (600 μA + 10 μA (I/O) + 50 μA (LDO enabled) + 40 μA (buffer)).

2.3.9.2 CC2640R2F Current Consumption

The net total of the current supplied to the CC2640R2F device is taken as 10 mA, including peripherals and TX only. A 50- μ A average current is chosen at VDDS2/3.

Measured on the TI CC2650EM-5XD reference design with $T_c = 25^\circ\text{C}$, $V_{\text{DDS}} = 3.0$ V with an internal DC/DC converter, unless otherwise noted.

Table 11. Power Consumption for CC2640R2F

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
I_{core}	Core current consumption	Reset. RESET_N pin asserted or VDDS below Power-on-Reset threshold	100			nA
		Shutdown. No clocks running, no retention	150			
		Standby. With RTC, CPU, RAM and (partial) register retention. RCOSC_LF	1.1			
		Standby. With RTC, CPU, RAM and (partial) register retention. XOSC_LF	1.3			
		Standby. With Cache, RTC, CPU, RAM and (partial) register retention. RCOSC_LF	2.8			μA
		Standby. With Cache, RTC, CPU, RAM and (partial) register retention. XOSC_LF	3.0			
		Idle. Supply Systems and RAM powered.	550			
		Active. Core running CoreMark	1.45 mA + 31 $\mu\text{A}/\text{MHz}$			
		Radio RX ⁽¹⁾	5.9			
		Radio RX ⁽²⁾	6.1			
I_{peri}	Radio TX, 0-dBm output power ⁽¹⁾	6.1				
	Radio TX, 5-dBm output power ⁽²⁾	9.1				
Peripheral Current Consumption (Adds to core current I_{core} for each peripheral unit activated) ⁽³⁾						
Peripheral power domain	Delta current with domain enabled	20			μA	
I_{peri}	Serial power domain	Delta current with domain enabled	13			μA
	RF Core	Delta current with power domain enabled, clock enabled, RF core idle	237			μA
	μDMA	Delta current with clock enabled, module idle	130			μA
	Timers	Delta current with clock enabled, module idle	113			μA
	I^2C	Delta current with clock enabled, module idle	12			μA
	I _S S	Delta current with clock enabled, module idle	36			μA
	SSI	Delta current with clock enabled, module idle	93			μA
	UART	Delta current with clock enabled, module idle	164			μA

⁽¹⁾ Single-ended RF mode is optimized for size and power consumption. Measured on CC2650EM-4XS.

⁽²⁾ Differential RF mode is optimized for RF performance. Measured on CC2650EM-5XD.

⁽³⁾ I_{peri} is not supported in Standby or Shutdown.

2.3.9.3 On-State Current Calculations

The reflected current on the input side of the TPS61099 device is given in [Equation 13](#).

$$I_{TPS61099} = \frac{V_O \times I_O}{V_{imin} \times \eta} = \frac{4.2 \times 5 \text{ mA}}{1.8 \times 0.85} = 13.725 \text{ mA} \quad (13)$$

Where efficiency is taken to be 85% (maximum 88% at low load of 10 μA), see [Equation 14](#).

$$I_{TPS63036} = \frac{V_O \times I_O}{V_{imin} \times \eta} = \frac{2.1 \times 180 \mu\text{A}}{1.8 \times 0.5} = 420 \mu\text{A} \quad (14)$$

Where efficiency is taken to be 50%. Therefore, the net total current from all the branch is given in [Equation 15](#).

$$I_{net} = 13.725 \text{ mA} + 0.42 \text{ mA} + 12 \text{ mA} = 26.145 \text{ mA} \quad (15)$$

Therefore, the calculated battery life of the coin cell is given in [Equation 16](#).

For CR3032, rating = 500 mAh

$$\text{Life(hr)} = 500 \frac{\text{mAh}}{26.145 \text{ mA}} \times 0.85 = 16.255 \text{ hrs} \quad (16)$$

The measured currents on the TIDA-010029 device are much less than these calculated values because the calculations are for worst-case performance. The measured values are as follows.

$$I_{net} = 4.09 \text{ mA} \text{ at } V_{in} = 3 \text{ V}$$

$$I_{net} = 6.05 \text{ mA} \text{ at } V_{in} = 1.8 \text{ V}$$

So $I_{avg} = 5.06 \text{ mA}$, which gives battery life of 98.7 hours.

2.3.9.4 Off-State Current Calculations (Considering Battery Voltage = 3 V)

The RX_SUP current at low-power operation (15 μA at software power-down mode and 1 μA at hardware power-down mode) = 16 μA (worst case). The TX_SUP current at low-power operation (1 μA at software power-down mode, 1 μA at hardware power-down mode) = 2 μA (worst case). The net total current supplied to the CC2640R2F device is taken as 200 nA (shutdown), 5 μA (standby), and 550 μA (idle).

Reflected current on the input side of TPS61099 is:

$$I_{TPS61099} = \frac{V_O \times I_O}{V_{imin} \times \eta} = \frac{4.2 \times 2 \mu\text{A}}{1.8 \times 0.85} = 5.62 \mu\text{A} \quad (17)$$

$$I_{TPS63036} = \frac{V_O \times I_O}{V_{imin} \times \eta} = \frac{2.1 \times 2 \mu\text{A}}{1.8 \times 0.5} = 22 \mu\text{A} \quad (18)$$

$$I_{net(\text{shutdown})} = 5.62 \mu\text{A} + 22 \mu\text{A} + 0.2 \mu\text{A} = 27.82 \mu\text{A} \quad (19)$$

$$I_{net(\text{standby})} = 5.62 \mu\text{A} + 22 \mu\text{A} + 5 \mu\text{A} = 32.62 \mu\text{A} \quad (20)$$

$$I_{net(\text{idle})} = 5.62 \mu\text{A} + 22 \mu\text{A} + 600 \mu\text{A} = 627.62 \mu\text{A} \quad (21)$$

[Table 12](#) lists the battery lifetime for the cases shown.

Table 12. Battery Life Calculations

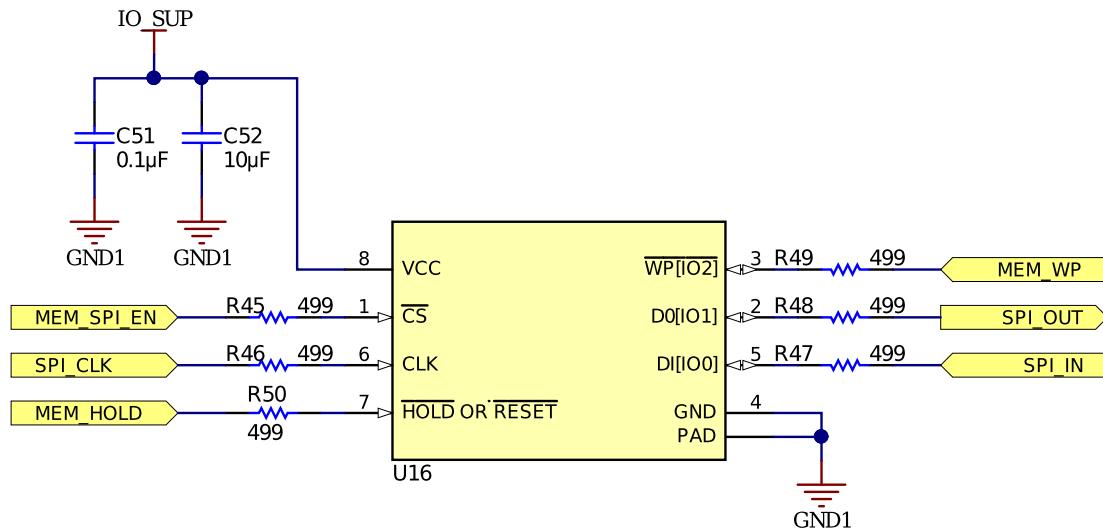
MODE	ON-STATE CURRENT (mA)	OFF-STATE CURRENT (μA)	BATTERY LIFE FOR 1 s/MIN DUTY CYCLE (DAYS)	BATTERY LIFE FOR 5 s/MIN DUTY CYCLE (DAYS)	BATTERY LIFE FOR 20 s/MIN DUTY CYCLE (DAYS)
Shutdown	4.09	27	220	57	15
Standby	4.09	32	209	56	15
Idle	4.09	627	30	22.7	11.7

2.3.10 External Memory

NOTE: U16 is currently not mounted on the TIDA-010029 board. It can be mounted if an external-data log memory is required. When selecting the memory, check the IO_SUP value and operating VCC for the memory.

The TIDA-010029 board has a provision for external memory connection over SPI, as shown in [Figure 19](#).

Figure 19. External Memory



[Table 13](#) lists the connections between the memory chip and the CC2640R2F device.

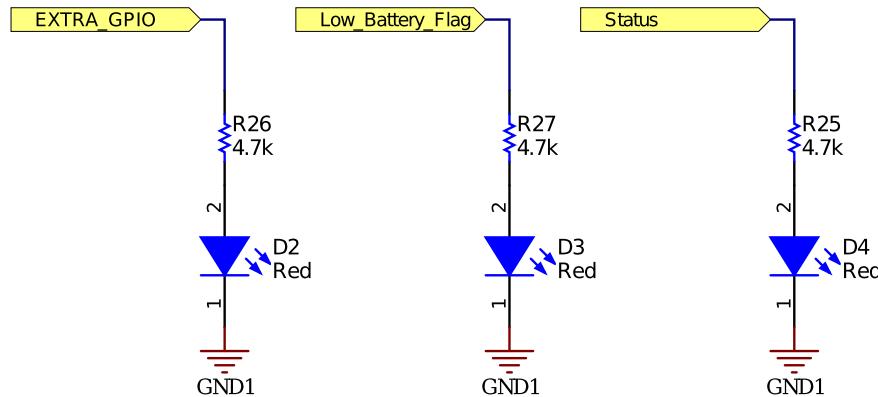
Table 13. Connections Between Memory and CC2640R2F

MEMORY PIN NUMBER	FUNCTION	CC2640R2F PIN NUMBER	FUNCTION	COMMENTS
1	/CS	18	DIO_12	Memory SPI enable
2	D0 (IO1)	15	DIO_9	SPI OUT for memory
3	/WP (IO2)	19	DIO_13	Memory write protect
5	D1 (IO0)	14	DIO_8	SPI IN for memory
6	CLK	16	DIO_10	SPI CLK for memory
7	/HOLD or /RESET	20	DIO_14	Memory hold

2.3.11 LED Indications

The board has three LEDs for indication, see [Figure 20](#) and [Figure 16](#).

Figure 20. LED Indications



[Table 14](#) lists the functions of each LED.

Table 14. LED Indications

LED NUMBER	COLOR	FUNCTION
D1	Green	Incoming power supply or battery indicator
D3	Red	Low-battery indication
D4	Red	BLE connection status

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

Figure 21 and Figure 22 show top and bottom views of the TIDA-010029 PCB, respectively. The important sections are highlighted with yellow boxes and captions.

Figure 21. TIDA-010029 PCB - Top View
Battery Holder (BT1) Not Mounted

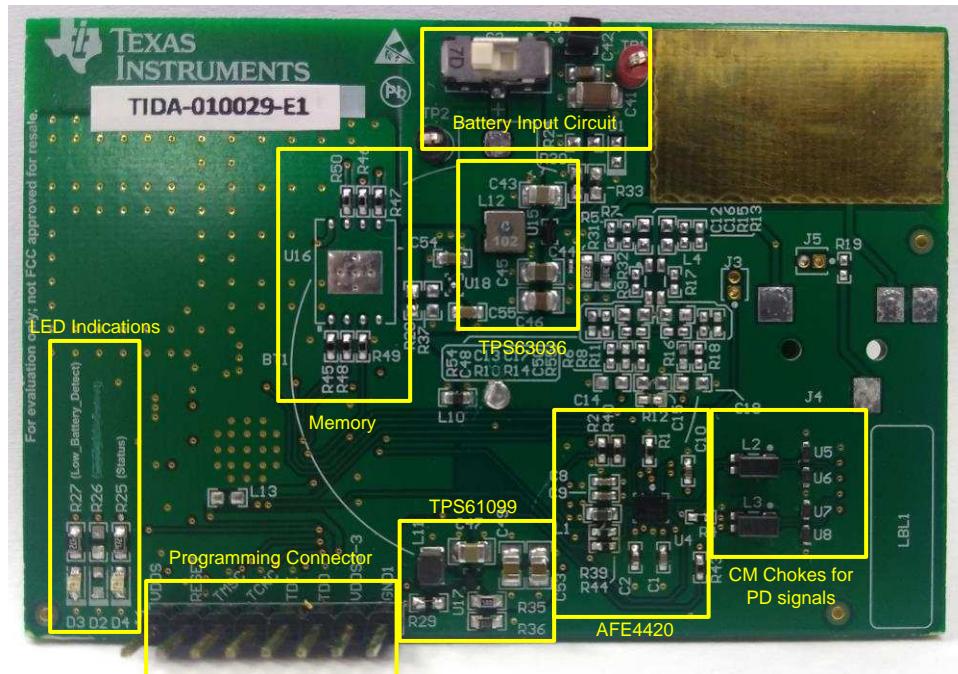
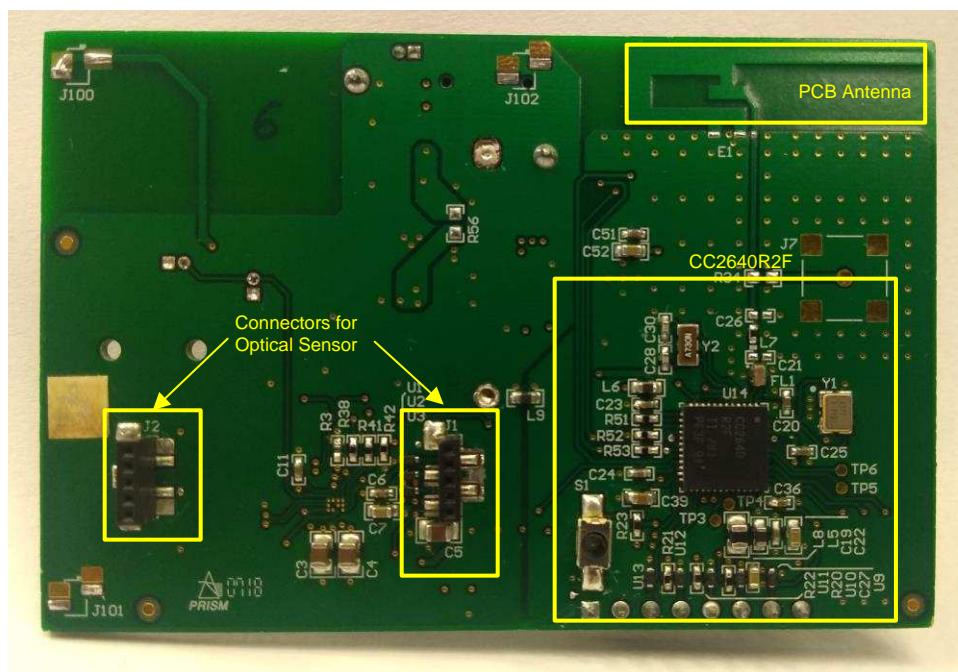


Figure 22. TIDA-010029 PCB - Bottom View



3.1.1.1 Connecting Optical Sensor Boards to Main Board

Figure 23 shows the PPG board mounted on the main board.

Figure 23. PPG Sensor Board Mounted on Main Board (Top View)

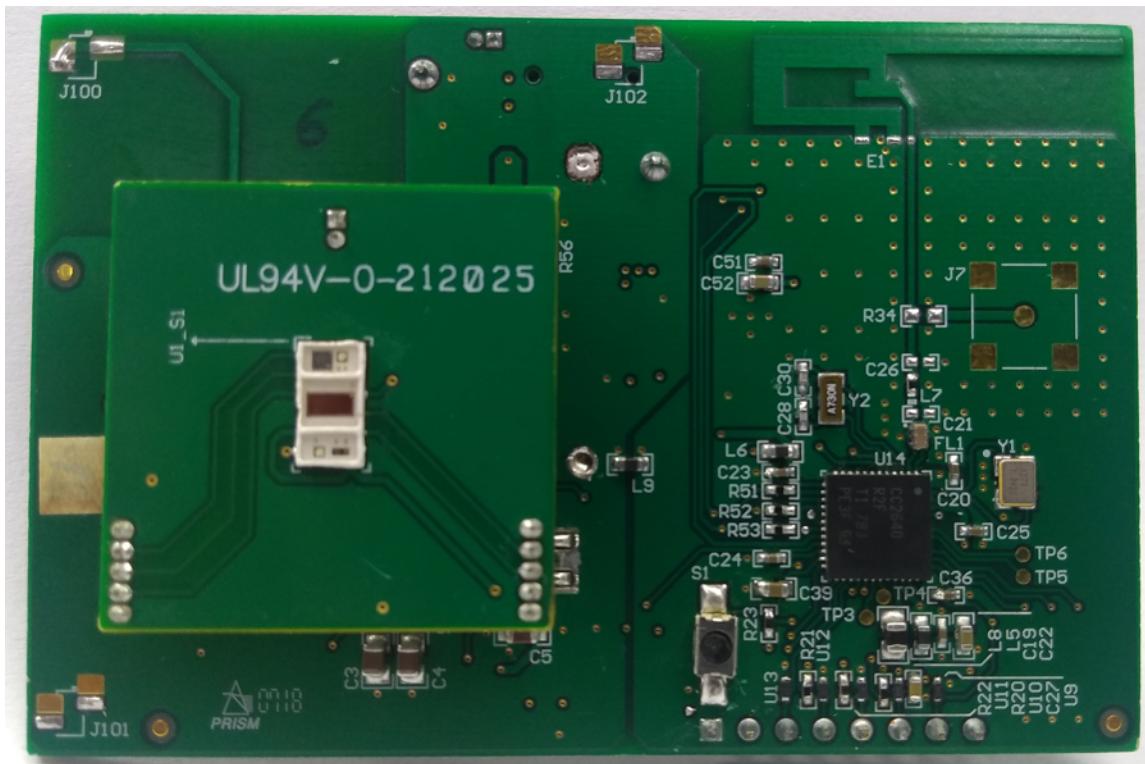


Figure 24 shows PPG sensor boards.

Figure 24. PPG Sensor Boards

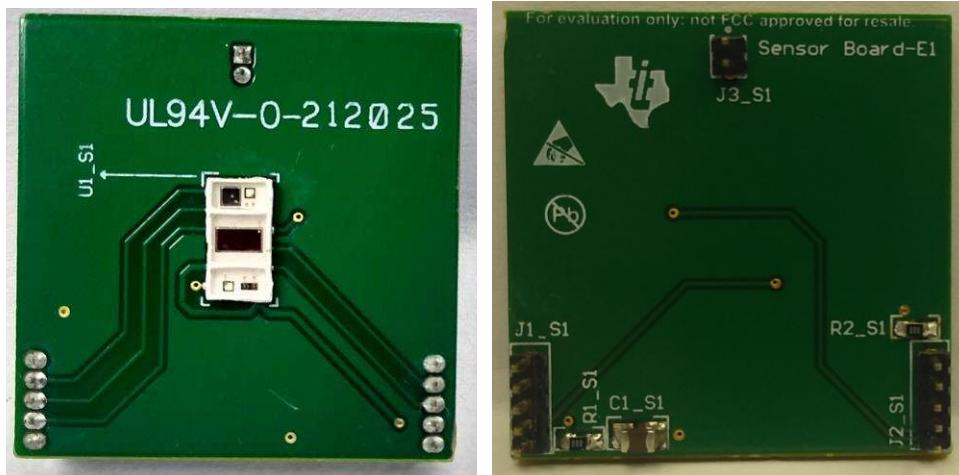
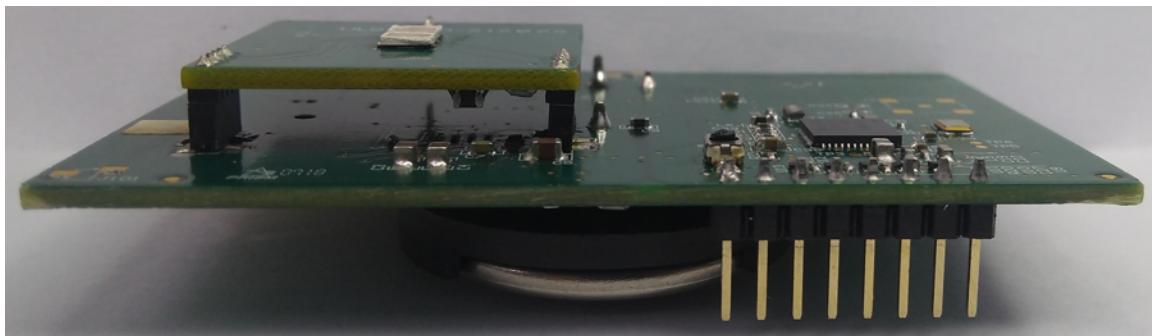


Figure 25. PPG Sensor Board Mounted on Main Board (Side View)



3.1.1.2 Configuration of PPG Sensor Boards

The PPG sensor board uses the SFH 7072 device from OSRAM. The default configuration for the PPG sensor board is as follows:

- LED1 (green1) of the SFH7072 = connected to TX4 of the AFE4420 device
- LED2 (green2) of the SFH7072 = not connected to the AFE4420 device
- LED3 (red) of the SFH7072 = connected to TX2 of the AFE4420 device
- LED4 (IR) of the SFH7072 = connected to TX3 of the AFE4420 device
- The Dual_PD_Enable bit is set in the 0x4E register in the AFE4420 device (see [Figure 26](#)).
- PD1 of the AFE4420 device is connected to Broadband PD, and PD2 of the AFE4420 device is connected to Infrared-Cut PD.

Figure 26. Timing and Settings for SFH 7072 PPG Sensor

Phase	PD2 Phase	PD1 Phase	Phase type	Active phase?	LED drv1 connects to	LED drv2 connects to		NUMAV	Rf	Cf	IOFFDAC (uA)	LED ON time	Stagger LED?	Mask Mode	FIFO data	FIFO count	LED current (per driver) (mA)	CONV width (us)	tWINDOW_MI
1		LED	LED	1	TX2			4	50	5	0	84	0	Never mask	0	1	0.585	237.25	
2	Ambient	Ambient	1					4	50	5	0	84	0	Never mask	0	1		237.25	0
3	Ambient	Ambient	1					4	50	5	0	84	0	Never mask	0	1		237.25	0
4	Ambient	Ambient	1					4	50	5	0	84	0	Never mask	0	1		237.25	0
5	LED	LED	1		TX3			1	50	5	0	84	0	Never mask	0	1	0.585	72.25	0
6	Ambient	Ambient	1					1	50	5	0	84	0	Never mask	0	1		72.25	84
7	Ambient	Ambient	1					1	50	5	0	84	0	Never mask	0	1		72.25	84
8	Ambient	Ambient	1					1	50	5	0	84	0	Never mask	0	1		72.25	84
9	LED		LED	1	TX4			1	50	5	0	84	0	Never mask	0	1	4.095	72.25	84
10	Ambient	Ambient	1					1	50	5	0	84	0	Never mask	0	1		72.25	84
11	Ambient		Ambient	1				1	50	5	0	84	0	Never mask	0	1		72.25	84
12	Ambient		Ambient	1				1	50	5	0	84	0	Never mask	0	1		72.25	84
13	Ambient		Ambient	1				1	50	5	0	84	0	Never mask	0	1		72.25	84
14	Ambient		Ambient	1				1	50	5	0	84	0	Never mask	0	1		72.25	84
15	Ambient		Ambient	1				1	50	5	0	84	0	Never mask	0	1		72.25	84
16	Ambient		Ambient	1				1	50	5	0	84	0	Never mask	0	1		72.25	84

NOTE: [Figure 26](#) is a screen shot from the AFE4420EVM GUI (available at [AFE4420EVM](#)).

3.1.2 Software

The following software tools were used to test and obtain the results for this TI reference design:

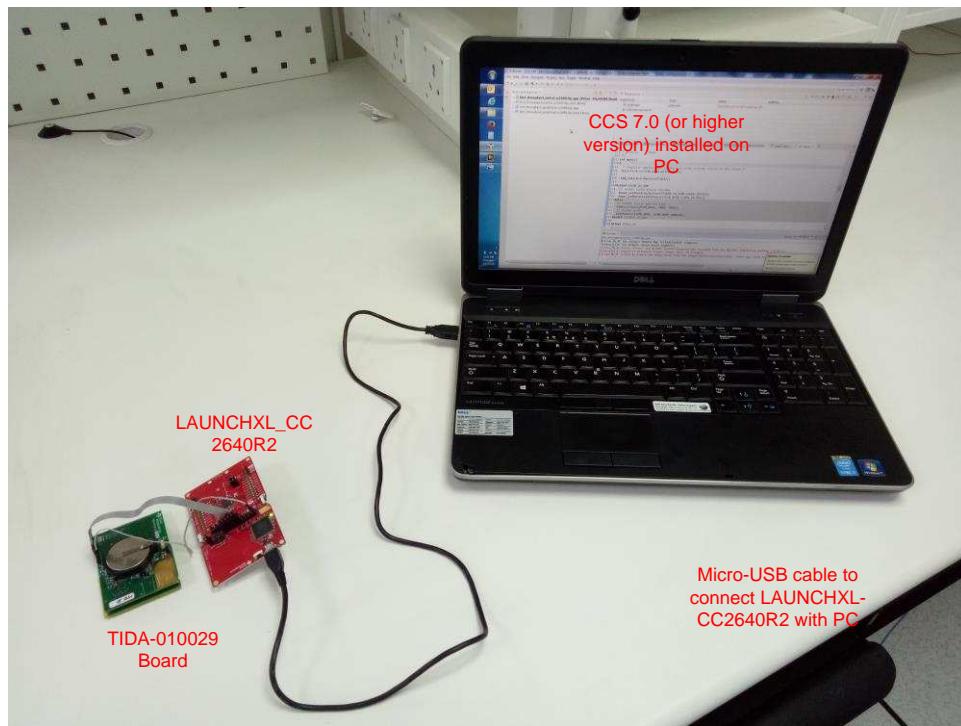
- Code Composer Studio™ (CCS), version 7 or higher (This software should be installed with CC26xx support. Run installer again if CC26xx support is not already installed.)
- SIMPLELINK-CC2640R2-SDK Software
- LAUNCHXL-CC2640R2
- LabVIEW™ 2016 Development Engine or Runtime Engine (32-bit)
- JAVA Runtime Engine (32-bit)

The following instructions are for PCs that CCS, SIMPLELINK-CC2640R2-SDK, LabVIEW and JAVA are already installed. Download the LabVIEW application setup (zip file) from the [TIDA-010029 product page](#). This setup installs the firmware containing four project folders (two for the transmit section and two for the receive section) and the LabView application folder containing executable file and source files.

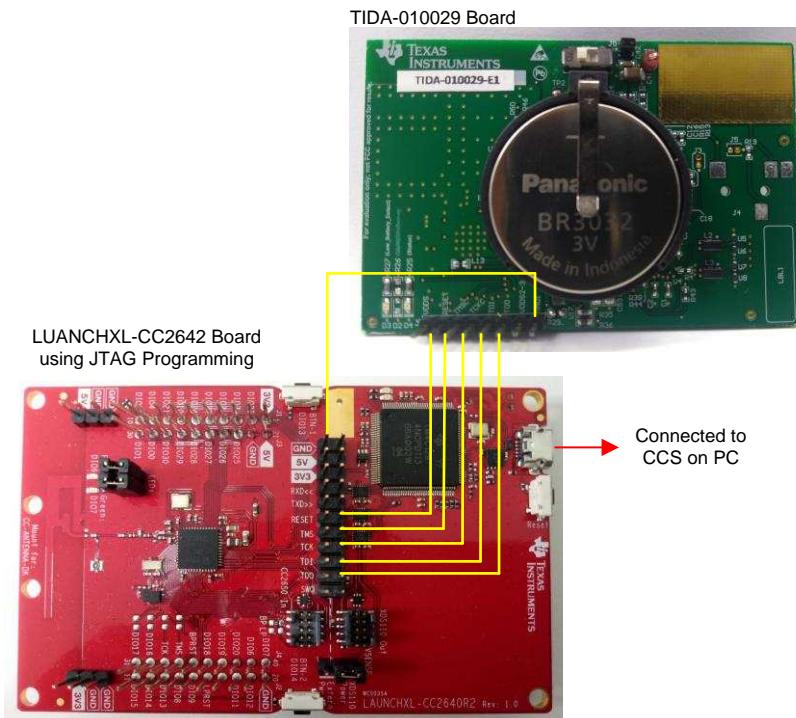
3.1.2.1 Software Loading for TIDA-010029 Board (Transmit Side of BLE)

1. Plug in the LAUNCHXL-CC2640R2 board on the USB port of the PC. See the setup in [Figure 27](#) and [Figure 28](#). [Table 15](#) lists the connections between the TIDA-010029 board and the LAUNCHXL-CC2640R2 board.

Figure 27. Programming TIDA-010029 Board Using LAUNCHXL-CC2640R2



2. Insert one CR3032 battery into the BT1 connector on the TIDA-010029 board, and power it on by using the S2 switch, and ensure J8 is shorted on the TIDA-010029 board.
3. Open CCS as administrator by right-clicking on the CCS icon and run as administrator.
4. Click on the Project option in the main toolbar and then click Import CCS projects.
5. Browse to select the installed firmware (Default: C:\Program Files (x86)\Texas Instruments\TIDA-010029\TIDA-010029_firmware) and import all projects. Click the OK button.
6. Click View, Project Explorer and select TIDA-010029_firmware_tx.
7. Click on the Run and Debug buttons. This action programs the board with the selected project file.
8. Disconnect the TIDA-010029 board from the LAUNCHXL-CC2640R2 device.

Figure 28. Connections Between TIDA-010029 Board and LAUNCHXL-CC2640R2

Table 15. Connections for Programming TIDA-010029 Using LAUNCHXL-CC2640R2

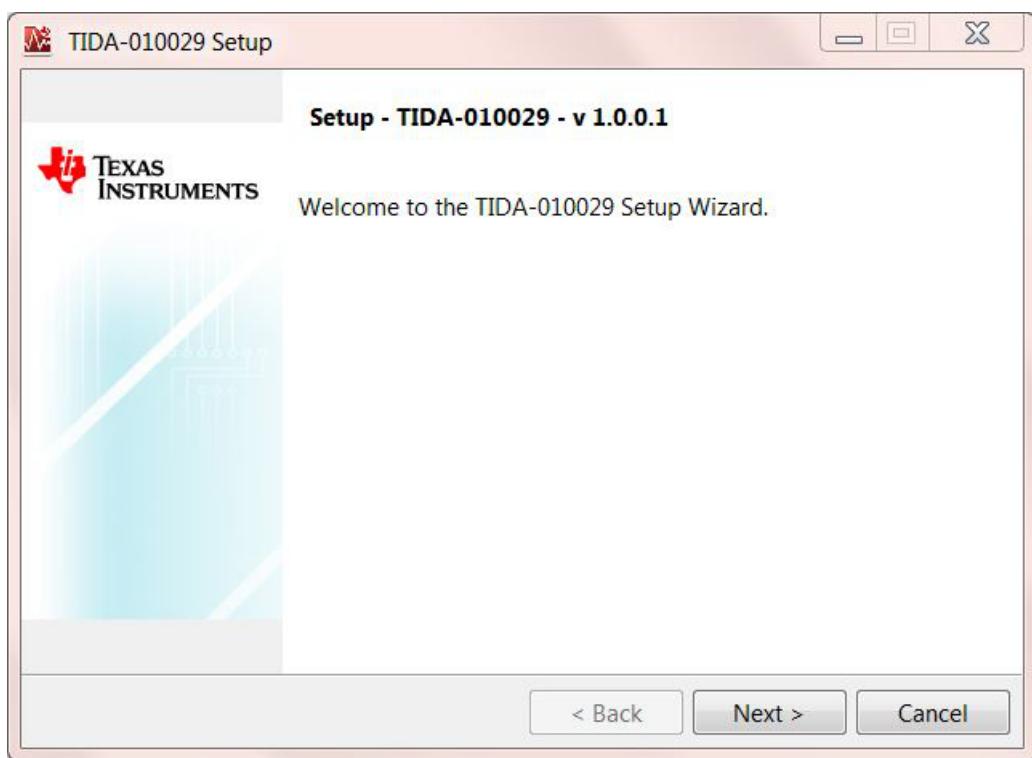
CONNECTION ON LAUNCHXL-CC2640R2 (ON XDS110 OUTSIDE)	PIN NO.	CONNECTION ON TIDA-010029 BOARD (CONNECTOR J6)	PIN NO.
GND	1	GND	1
RESET	6	CC_RESET	7
TMS	7	JTAG_TMSC	6
TCK	8	JTAG_TCKC	5
TDI	9	TDI	4
TDO	10	TDO	3

3.1.2.2 LabVIEW™ File Execution for Checking Measurement Data (Receive Side of BLE)

NOTE: Only one device, the LAUNCHXL-CC2640R2 or XDS110, can be connected to the PC while running the executable file.

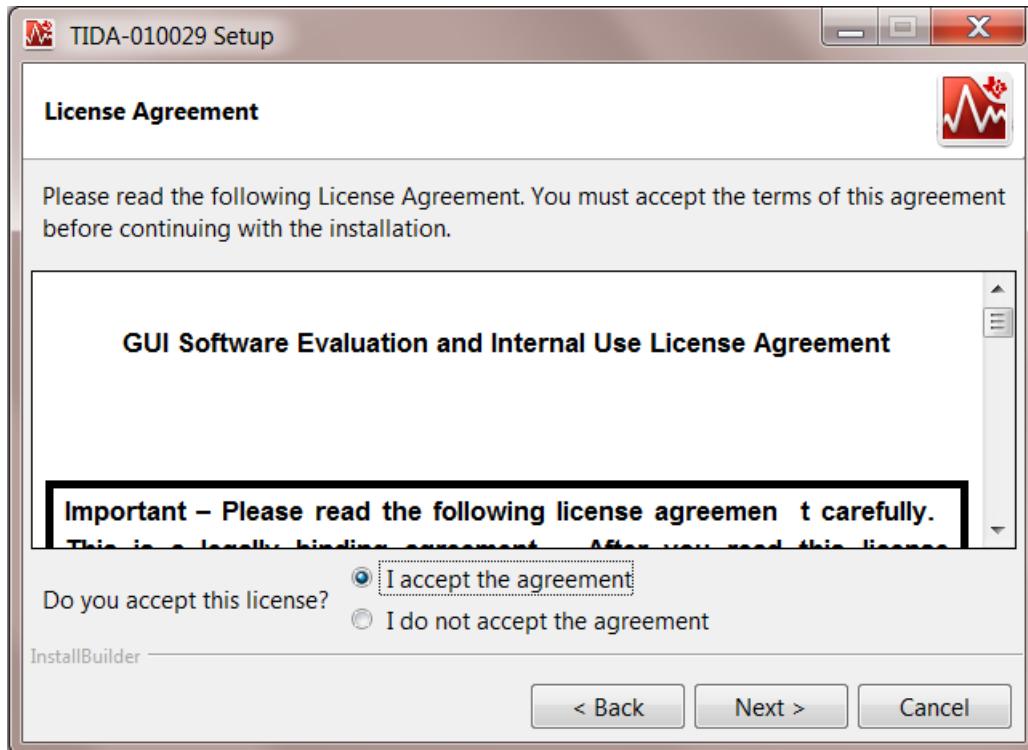
1. Insert one CR3032 battery into the BT1 connector on the TIDA-010029 board and power it on by using the S2 switch. Ensure J8 is shorted on the TIDA-010029 board. Ignore this step if it was already done during programming of the TIDA-010029 board.
2. Revert back to the original LaunchPAD jumper settings.
3. Plug in the LAUNCHXL-CC2640R2 device on the USB port of the PC.
4. Open the Setup_TIDA-010029.exe file and go through the installation process, explained as follows.
 1. Click Next on the Setup Welcome screen shown in [Figure 29](#).

Figure 29. Setup Welcome Screen



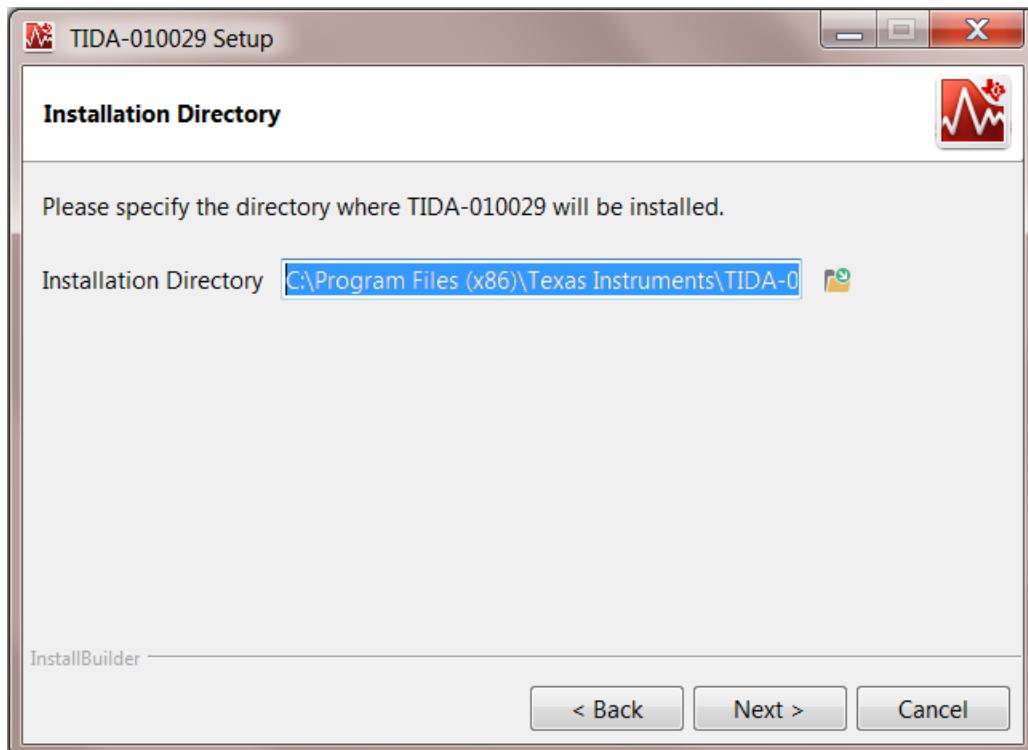
- Accept the agreement and click Next on the License Agreement screen shown in [Figure 30](#).

Figure 30. License Agreement Screen



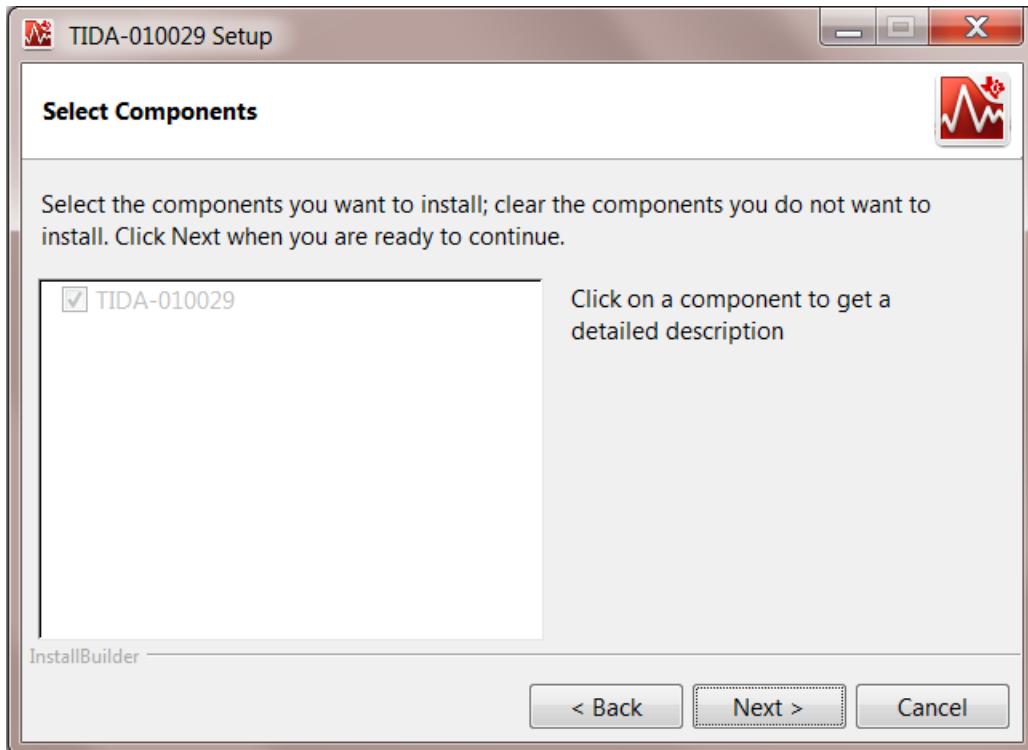
- Click Next on the Installation Directory screen shown in [Figure 31](#).

Figure 31. Installation Directory Screen



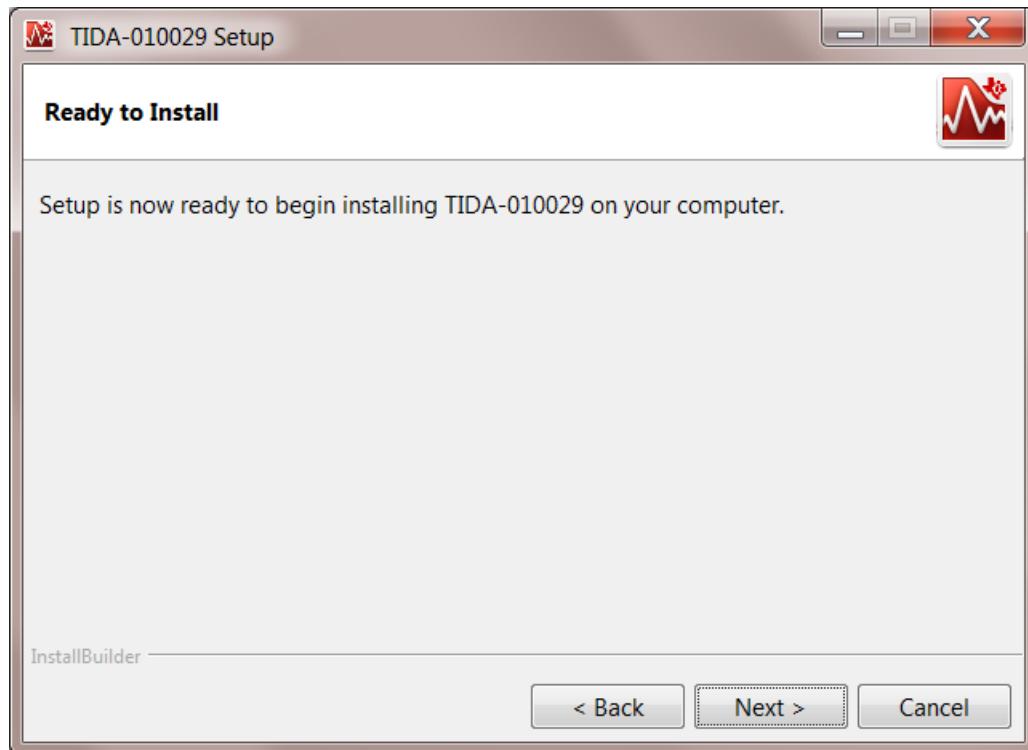
4. Click Next on the Select Components screen shown in [Figure 32](#).

Figure 32. Select Components Screen



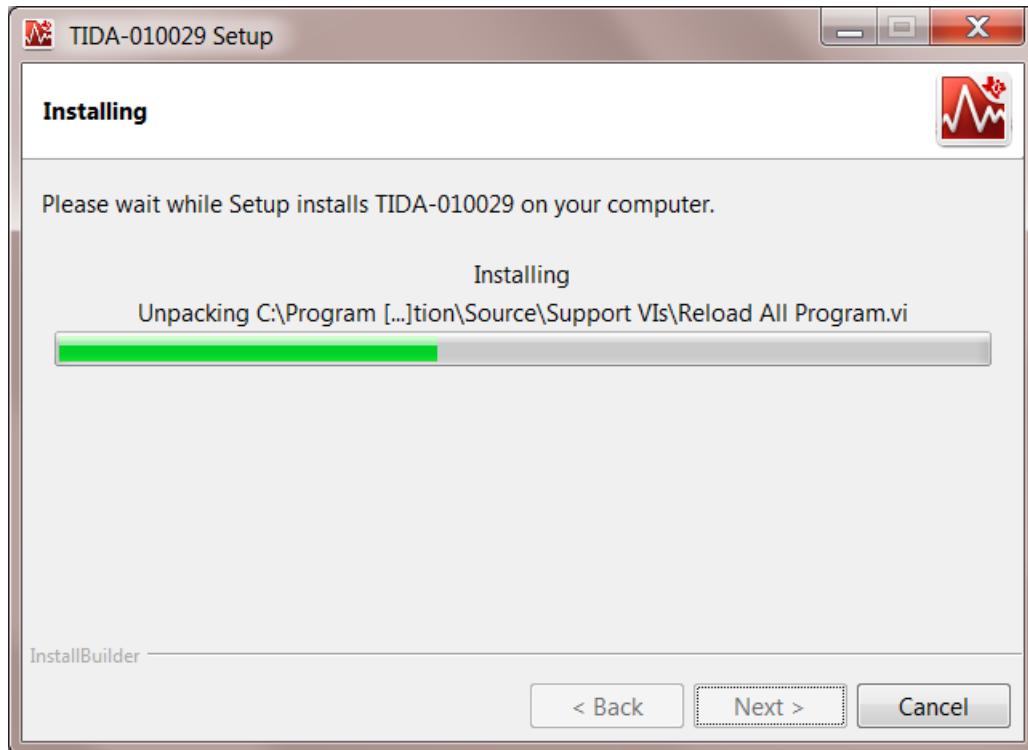
5. Click Next on the Ready to Install screen as shown in [Figure 33](#).

Figure 33. Ready to Install Screen

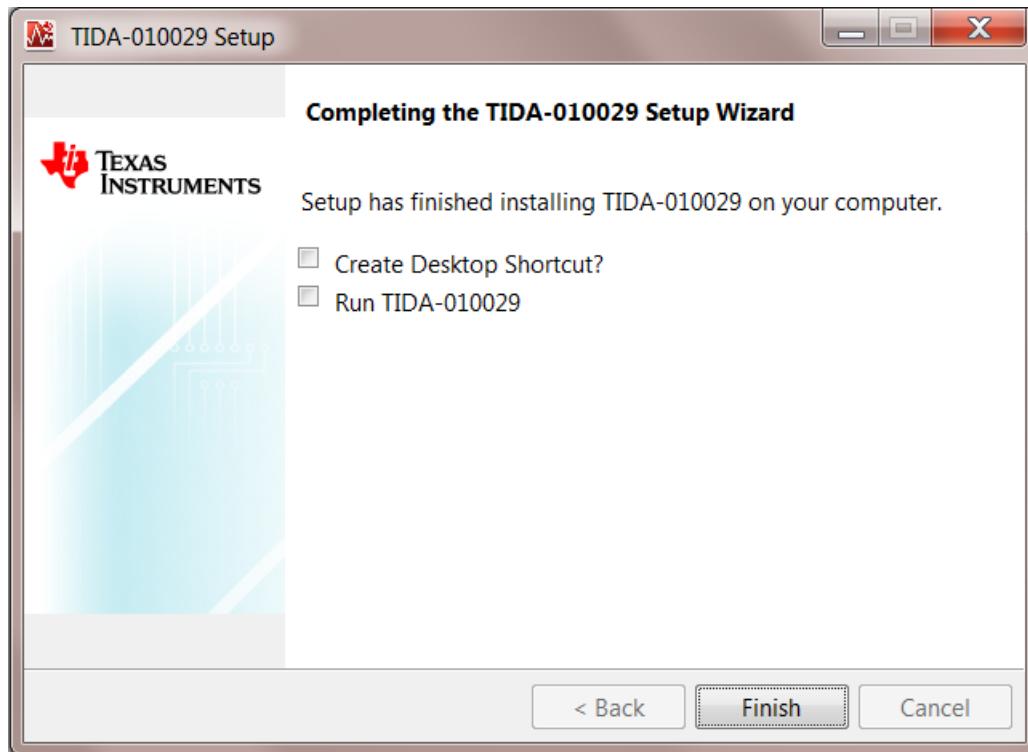


The setup starts installing and the progress screen is displayed as shown in [Figure 34](#).

Figure 34. Installing GUI

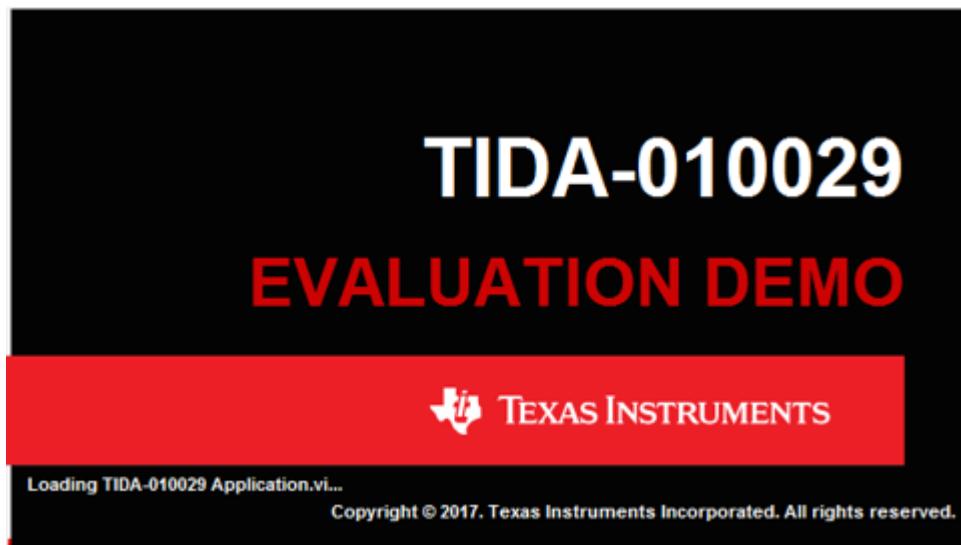


6. When installed, click Finish. Look for the TIDA-010029 Application.exe at the installed location (default location: C:\Program Files (x86)\Texas Instruments\TIDA-010029\TIDA-010029 Application).

Figure 35. Completing TIDA-010029 Setup Wizard

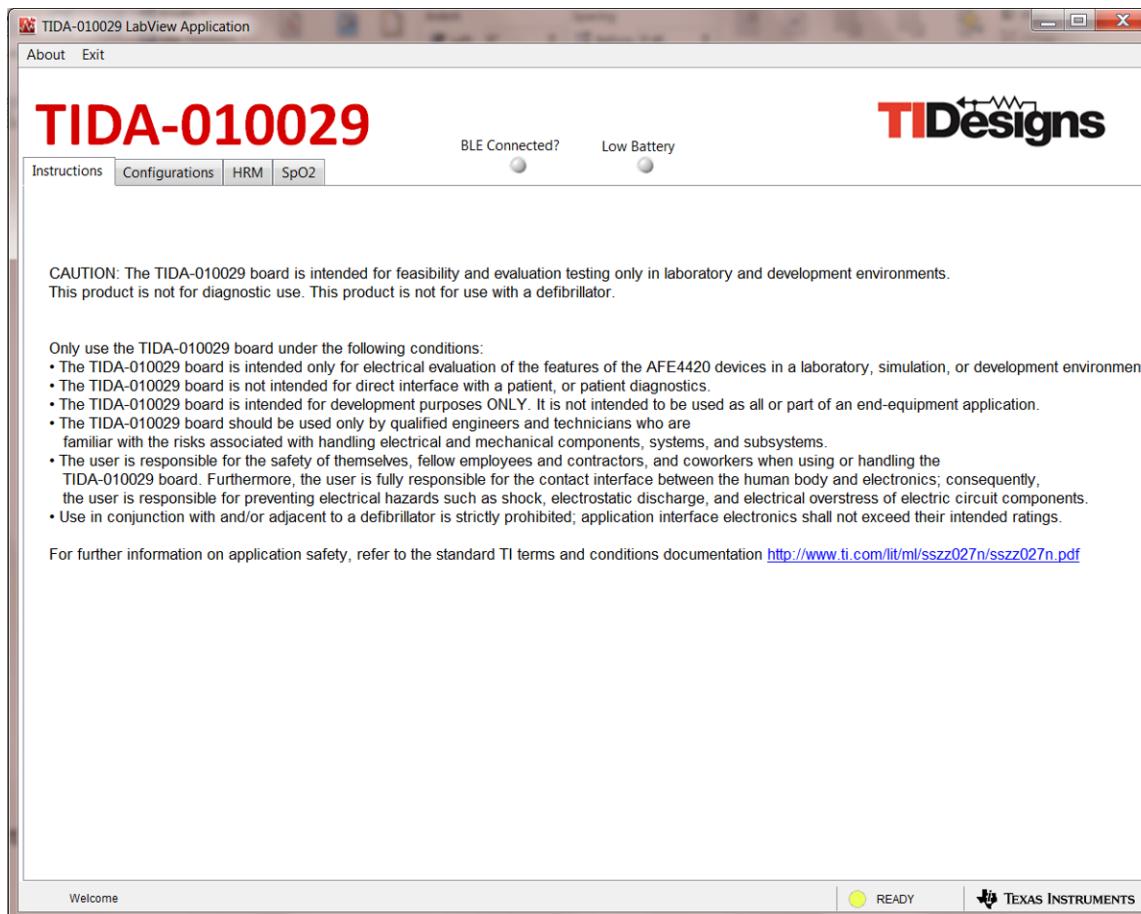
While launching the GUI, a splash screen appears, as shown in [Figure 36](#).

Figure 36. Splash Screen on Launching TIDA-010029 GUI



The Instructions tab provides instructions and safety precautions as shown in [Figure 37](#).

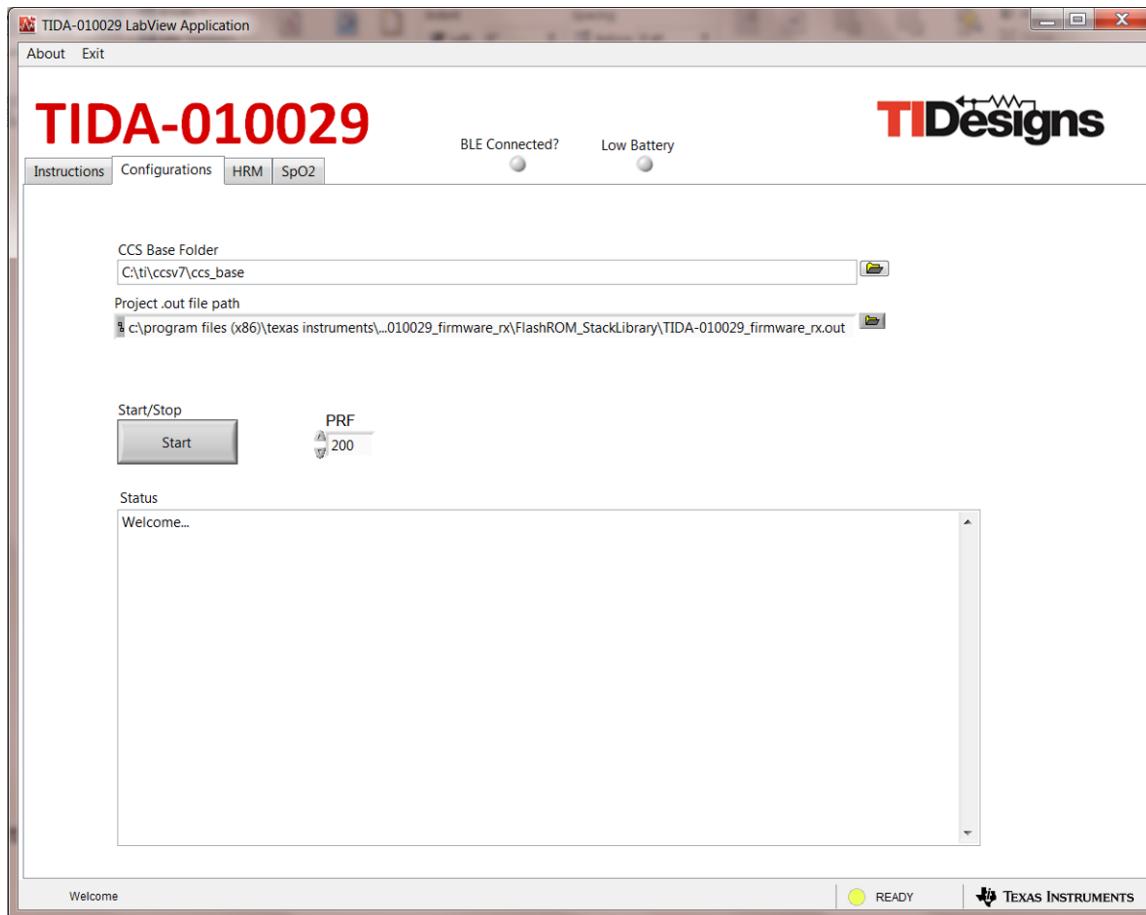
Figure 37. TIDA-010029 GUI Instructions Tab



The Configurations tab shown in [Figure 38](#) provides information about the software paths.

1. Ensure that the CCS base-folder path is set to <CCS installation path>\ccsv7\ccs_base.
2. Ensure that the project .OUT file path is set to <installation folder>\TIDA-010029_firmware\TIDA-010029_firmware_rx\FlashROM_StackLibrary\TIDA-010029_firmware_rx.out.
3. The START/STOP button can connect and program the LAUNCHXL-CC2640R2 device to capture the data. After clicking the START/STOP button, the TIDA-010029 board must immediately be power cycled using the S2 switch. The START/STOP button can also disconnect the link.
4. The Pulse Repetition Frequency (PRF) can be changed.

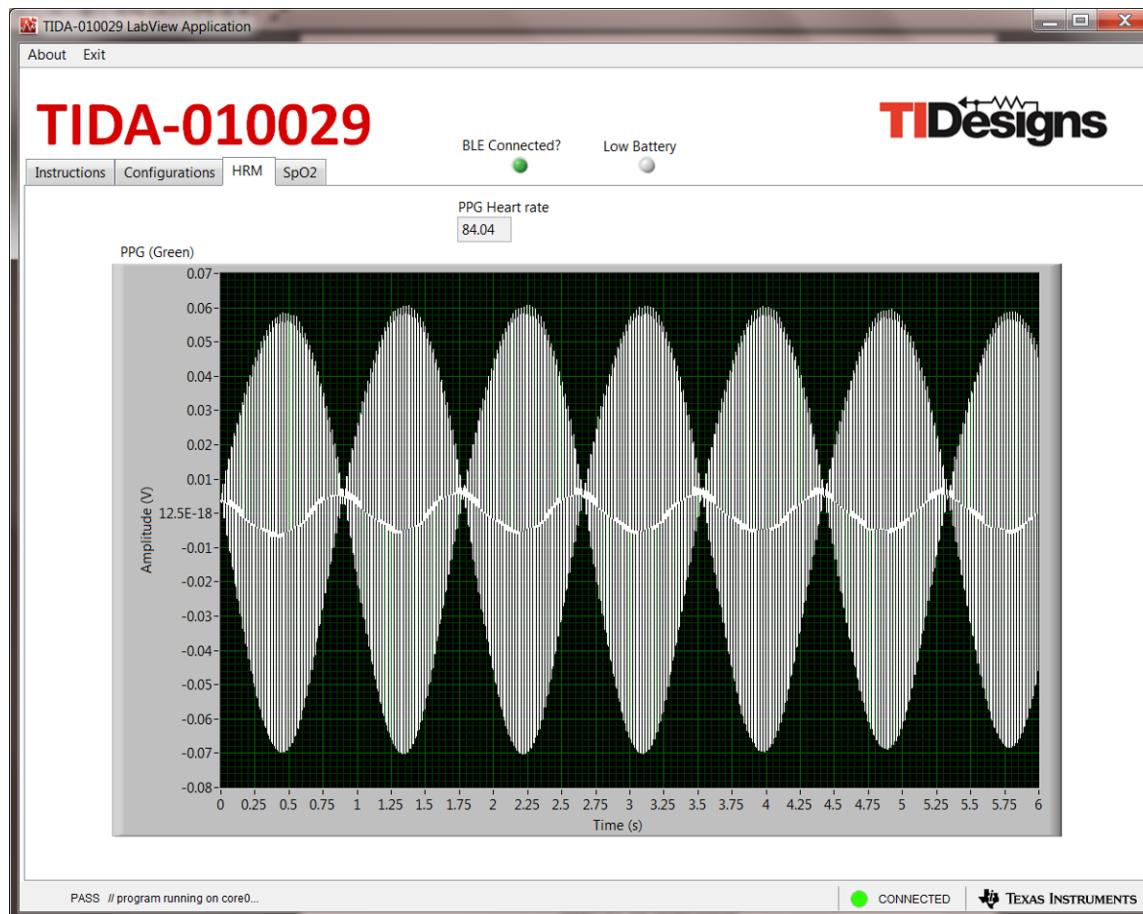
Figure 38. TIDA-010029 GUI Configurations Tab



The HRM tab shown in [Figure 39](#) shows PPG data taken from green LED. The HRM tab estimates heart rate from both sets of data (time difference in seconds between two peaks of PPG data / 60).

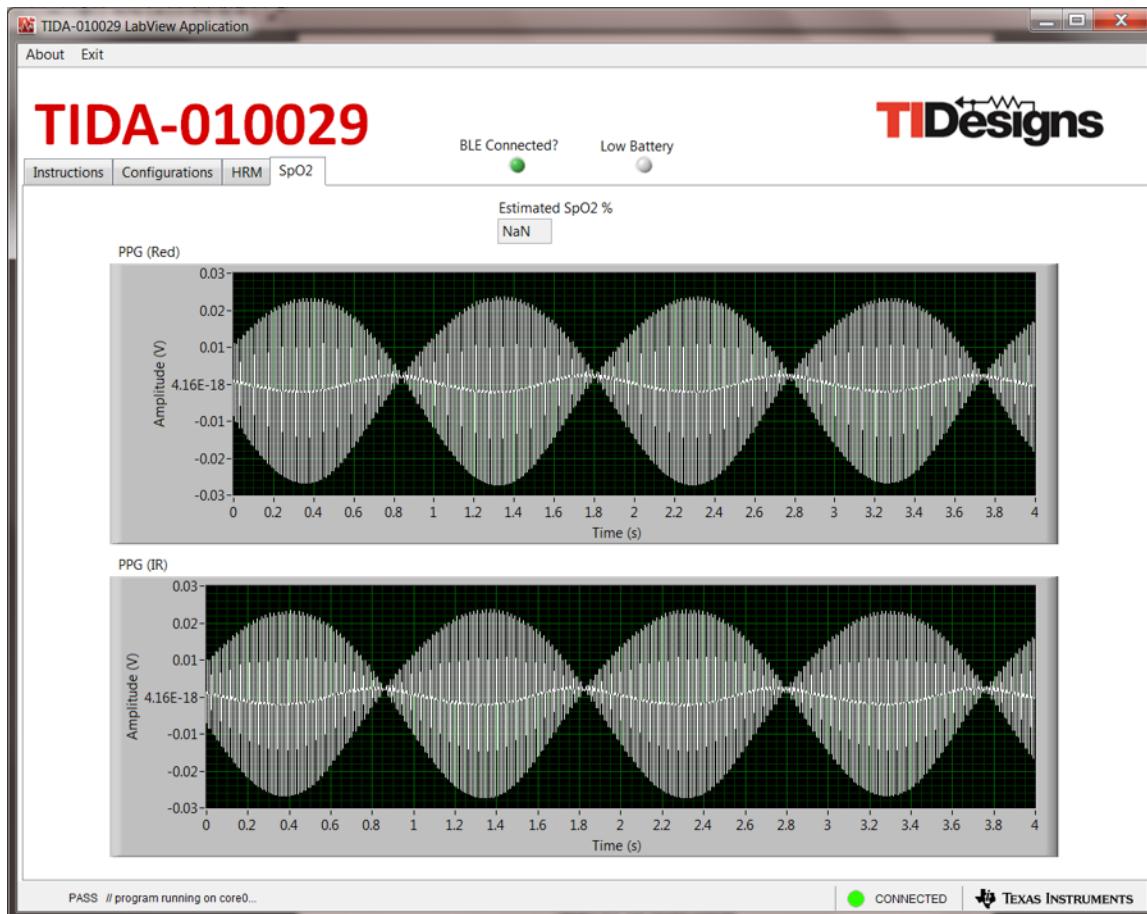
NOTE: As soon as the Bluetooth low energy connection is established, the Configurations tab switches to the HRM tab.

Figure 39. TIDA-010029 GUI HRM Tab



The SpO2 tab shown in [Figure 40](#) shows PPG data taken from the red and IR LEDs. The SpO2 tab estimates percentage of SpO2 from both sets of data.

Figure 40. TIDA-010029 GUI SpO2 Tab



- The LED indication of BLE Connected? turns on if the LAUNCHXL-CC2640R2 receiver is connected with the TIDA-010029 board over Bluetooth low energy.
- The LED indication of Low Battery turns on if the battery voltage is less than 2 V.
- The Exit button can disconnect and quit the .exe file.

3.2 Testing and Results

This section describes the test setup and test results for the TIDA-010029 board. [Figure 41](#) shows the test setup for capturing data.

Figure 41. Test Setup for Capturing Data



3.2.1 Test Setup

1. Plug in the LAUNCHXL-CC2640R2 device on the USB port of the PC.
2. Open the TIDA-010029 Application.exe file.
3. Connect the human body (fingers or wrist) to the TIDA-010029 board for the measurement. Ensure that the PPG sensor on the bottom side of the board is covered by a finger.
4. Ensure that the paths are correct for the CCS Base Folder and Project .out file on the Configurations tab.
5. Click on the START/STOP button in the Configurations tab on the TIDA-010029 GUI.
6. Power-cycle the TIDA-010029 board by toggling the S2 switch.
7. The Configurations Tab shows the following message:

```
Welcome...
Advanced filtering is disabled in the Run Time Engine
PASS // core0 connected as Cortex_M3_0...
PASS // program file loaded on core0...
PASS // program running on core0...
```

As soon as the TIDA-010029 board connects to the receiving LAUNCHXL-CC2640R2 board, the BLE Connected? LED turns on, and the HRM tab should be open showing PPG (green LED). The SpO2 tab can be used for measuring PPG data from the red and IR LEDs.

8. Once evaluation is over, click on the START/STOP button in the Configurations tab. The tab shows the following message:

```
PASS // closing tcp session on port 1444..
```

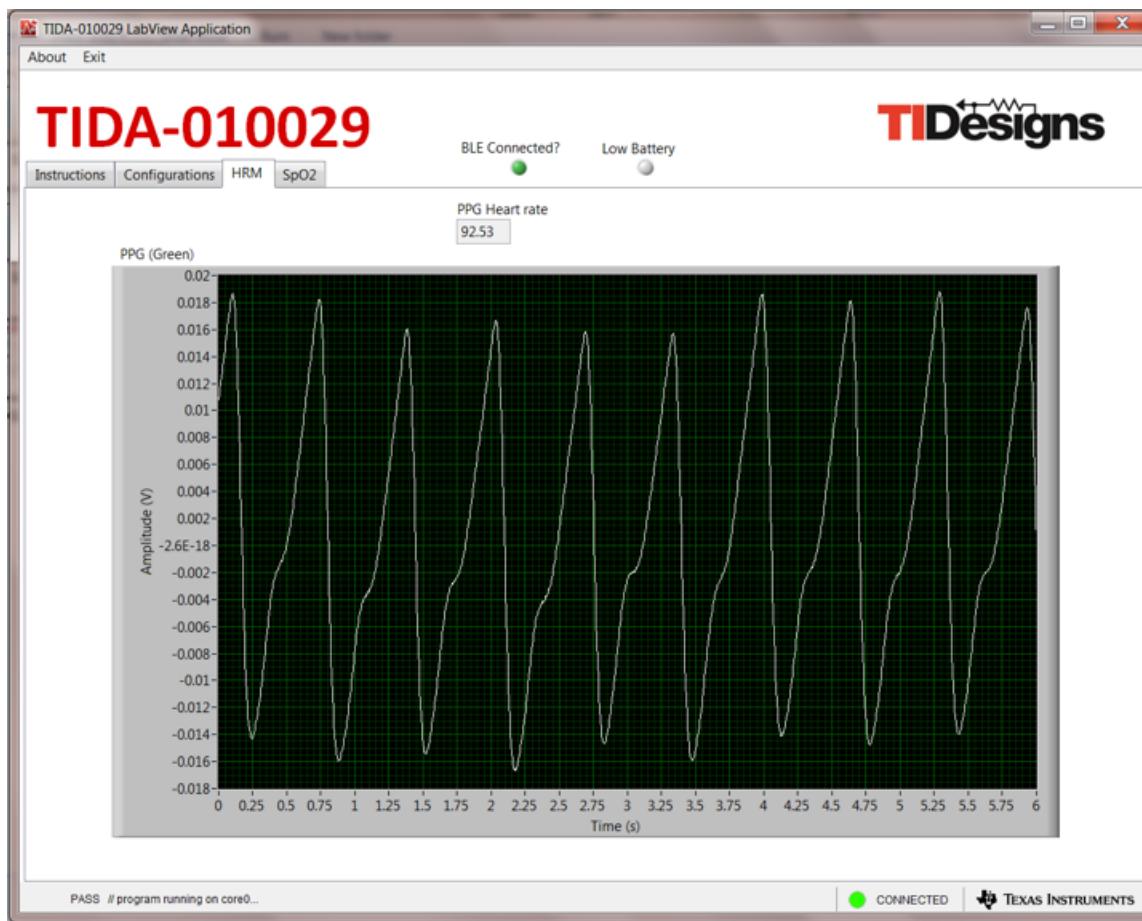
9. Click on the Exit button to quit the .exe file.

3.2.2 Test Results

3.2.2.1 Heart-Rate Measurement Using PPG (Green LED)

Figure 42 shows HRM data from the SFH 7072 sensor.

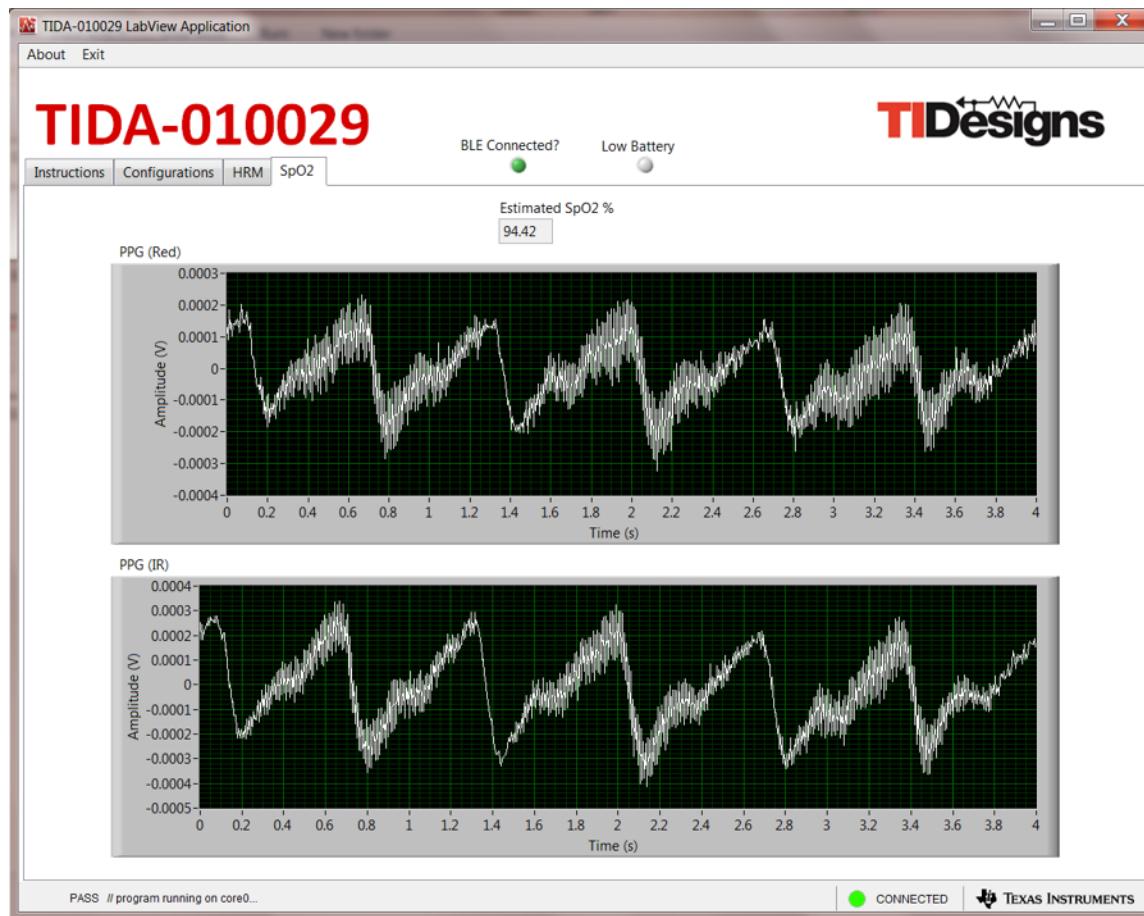
Figure 42. HRM Data From SFH 7072 Sensor



3.2.2.2 SpO₂ Measurement Using Red and IR LEDs

Figure 43 shows SpO₂ data from the SFH 7072 sensor.

Figure 43. SpO₂ Data From SFH 7072 Sensor



3.2.2.3

NOTE: During testing, it was observed that the power line noise and other motion artifacts getting coupled to the PPG signals drastically reduced the SNR. For HRM applications, it is imperative to remove the noise and baseline drift. Heart-rate estimation usually requires an algorithm that filters the noise and detects the beat-to-beat heart rate and average heart rate. Even under rest conditions, extraction of heart rate data can get complicated, due to sudden changes in the DC level of the signal, due to respiration and motion artifacts. The heart rate can be calculated by measuring the separation between the successive peaks of the signal after eliminating the effect of the sudden DC-level shifts. In the presence of artifacts such as motion, the PPG signal can be buried. This occurrence requires motion cancellation algorithms, usually aided by data from accelerometers, to be able to remove the motion artifact and extract the heart rate.

3.2.2.4 Low-Battery Indication

Low-battery indication is implemented on the TIDA-010029 board. The onboard LED D3 indicates the same. Low-battery is also highlighted on the TIDA-010029 GUI by turning on the LED. The low-battery detection threshold is set at 1.9 V.

3.2.2.5 Waveforms for DC/DC Converters

Figure 44 through Figure 48 show waveforms for DC/DC converters.

Figure 44. Waveform Showing Ibattery (Pink), RX_SUP (Yellow), TX_SUP (Green), and Vbattery (Purple)

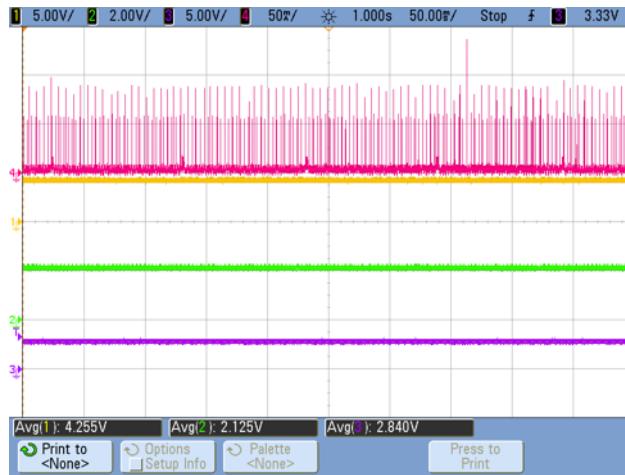


Figure 45. Waveform Showing Ibattery (Pink), Ripple on RX_SUP (Yellow), Ripple on TX_SUP (Green), and Ripple on Vbattery (Purple)

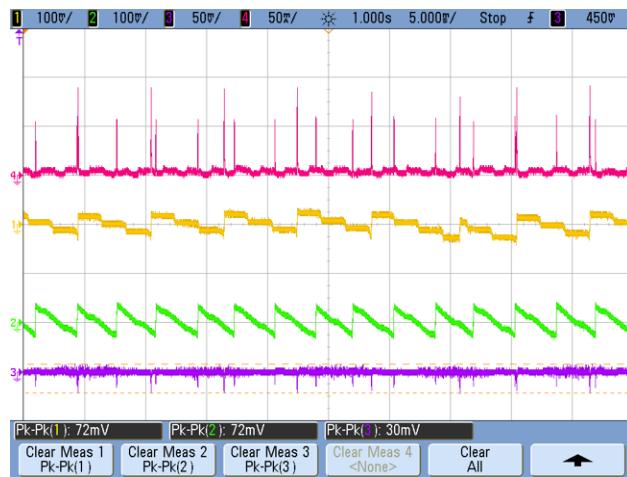


Figure 46. Pink Waveform Shows 100-ms Advertising Time for BLE



Figure 47. Three Pulses Showing Standard Advertising for BLE

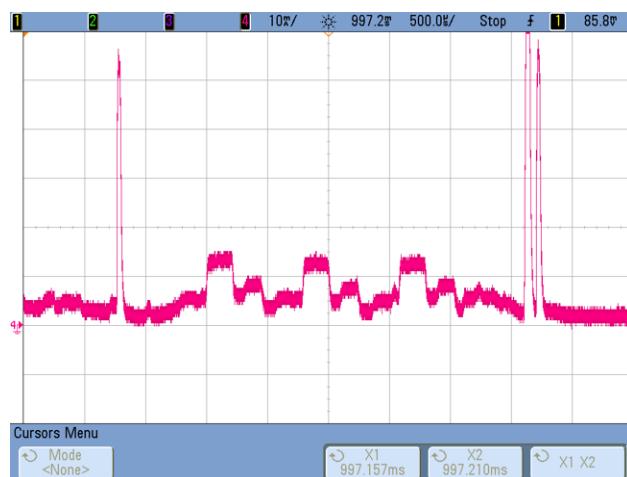
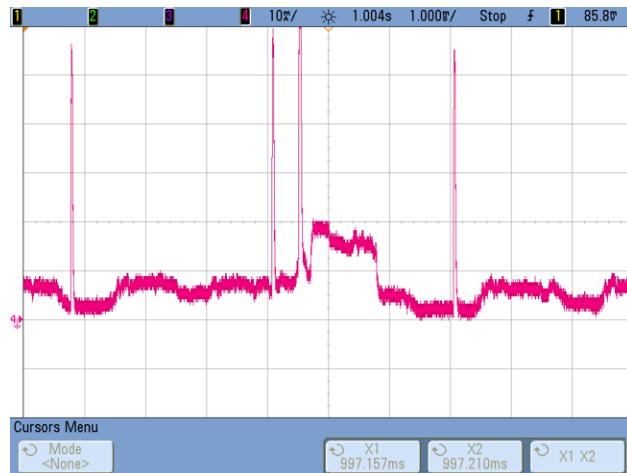


Figure 48. Pulse Showing Standard BLE Once Connected



3.2.2.6 Battery Life Test

The battery life test is done by keeping the TIDA-010029 board on for continuous transmission of the data. The CR3032 battery works continuously for 100 hours.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-010029](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-010029](#).

4.3 PCB Layout Recommendations

Device-specific layout guidelines for each TI part used in this design can be found in the corresponding data sheets. [Figure 49](#) and [Figure 50](#) show top and bottom views of the TIDA-010029 PCB, respectively.

4.3.1 Layout for Main Board

Figure 49. Top Layer for TIDA-010029 Board

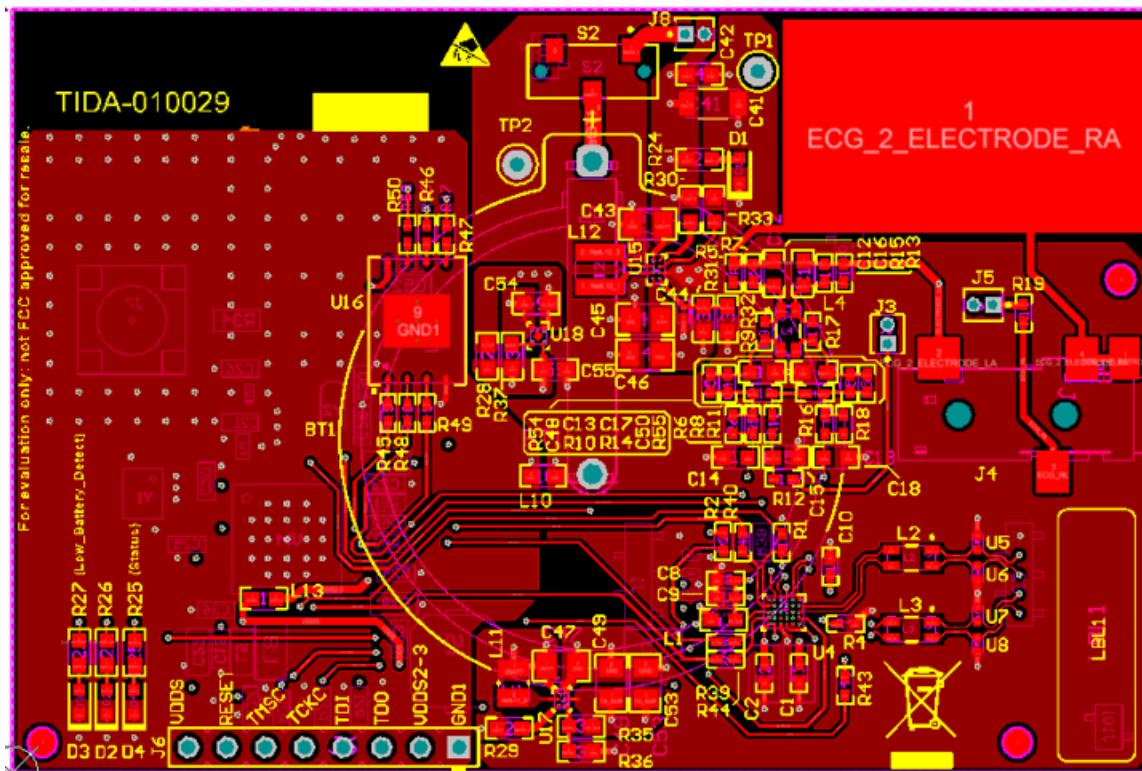


Figure 50. Bottom Layer for TIDA-010029 Board

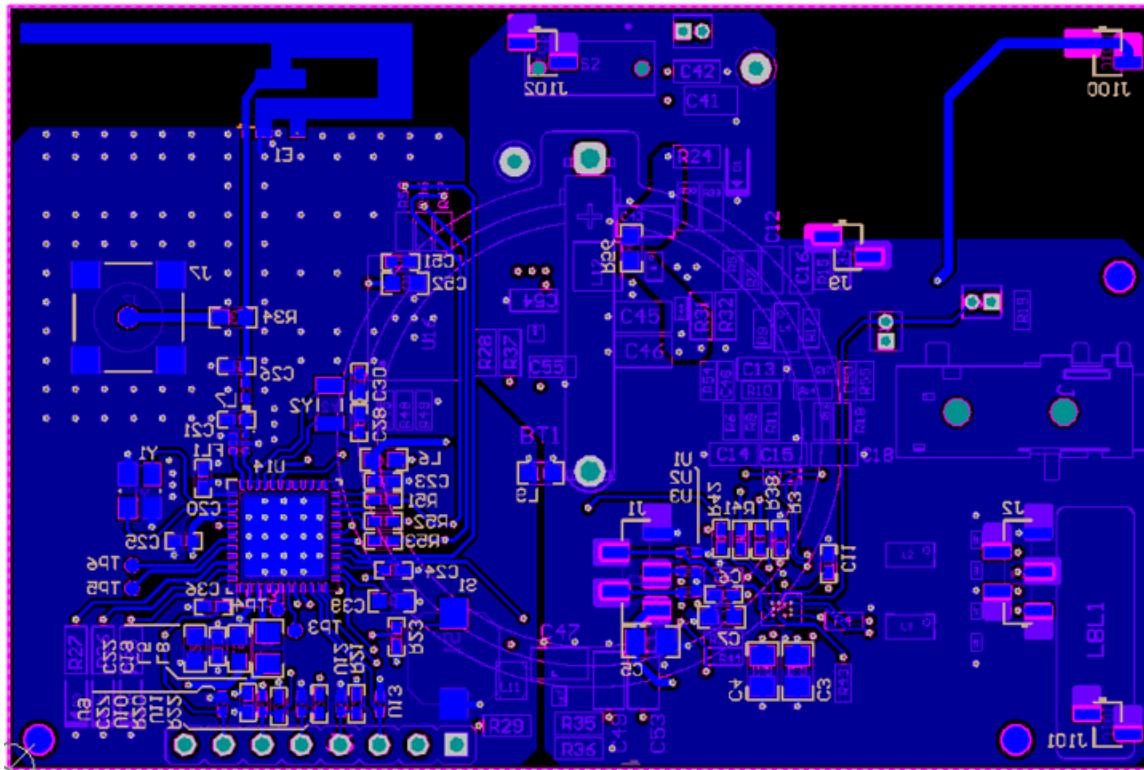


Figure 51. Power Layer for TIDA-010029 Board

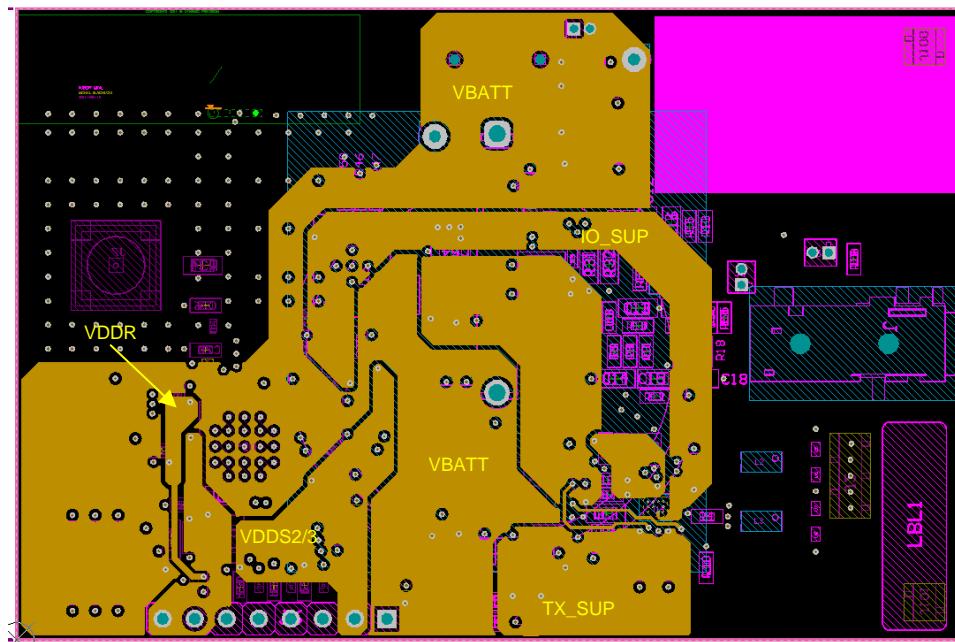
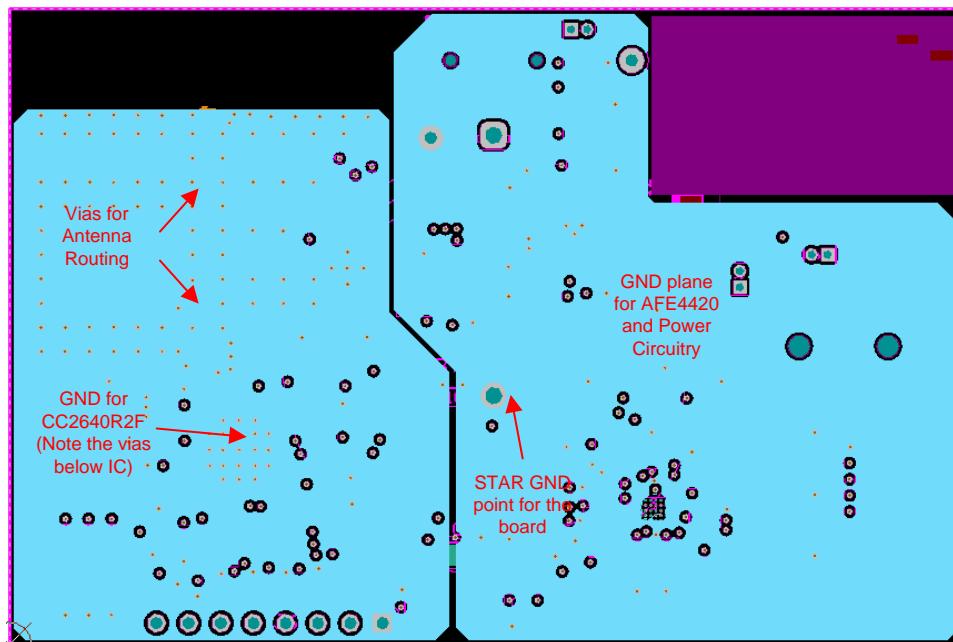
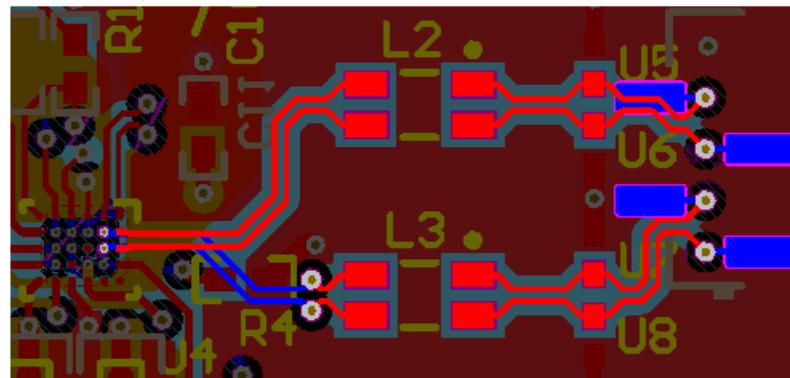


Figure 52. Ground Layer for TIDA-010029 Board



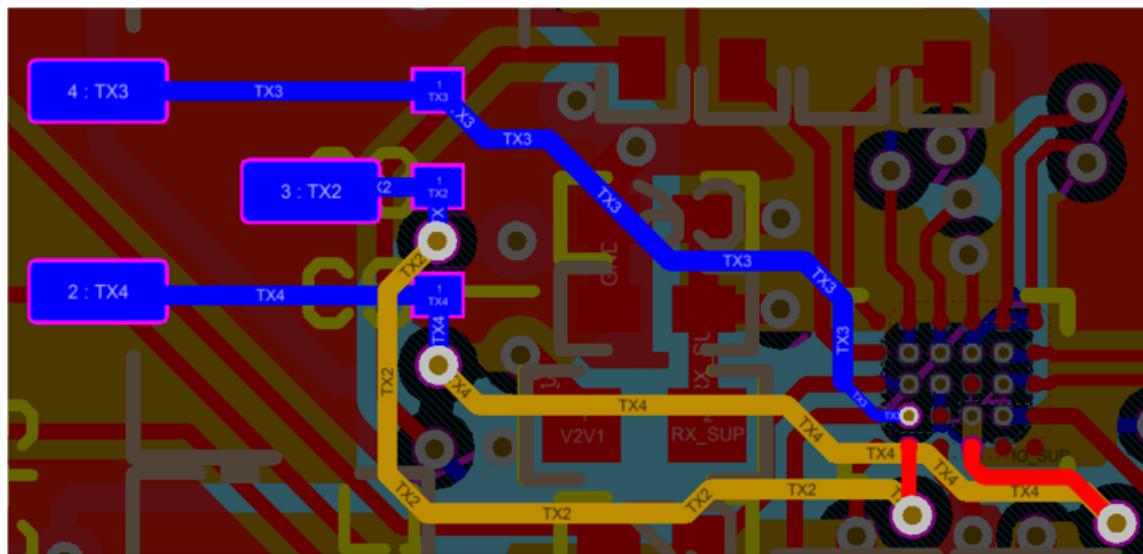
4.3.2 Connection From PDs to AFE

Figure 53. Traces From PDs to AFE



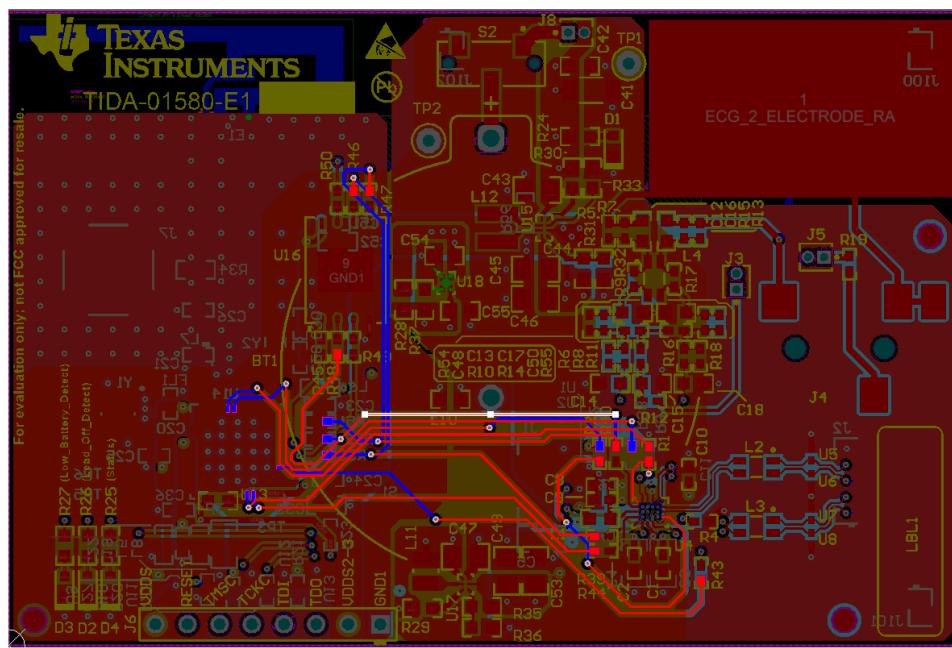
4.3.3 Connections From LEDs to AFE

Figure 54. Traces From LEDs to AFE



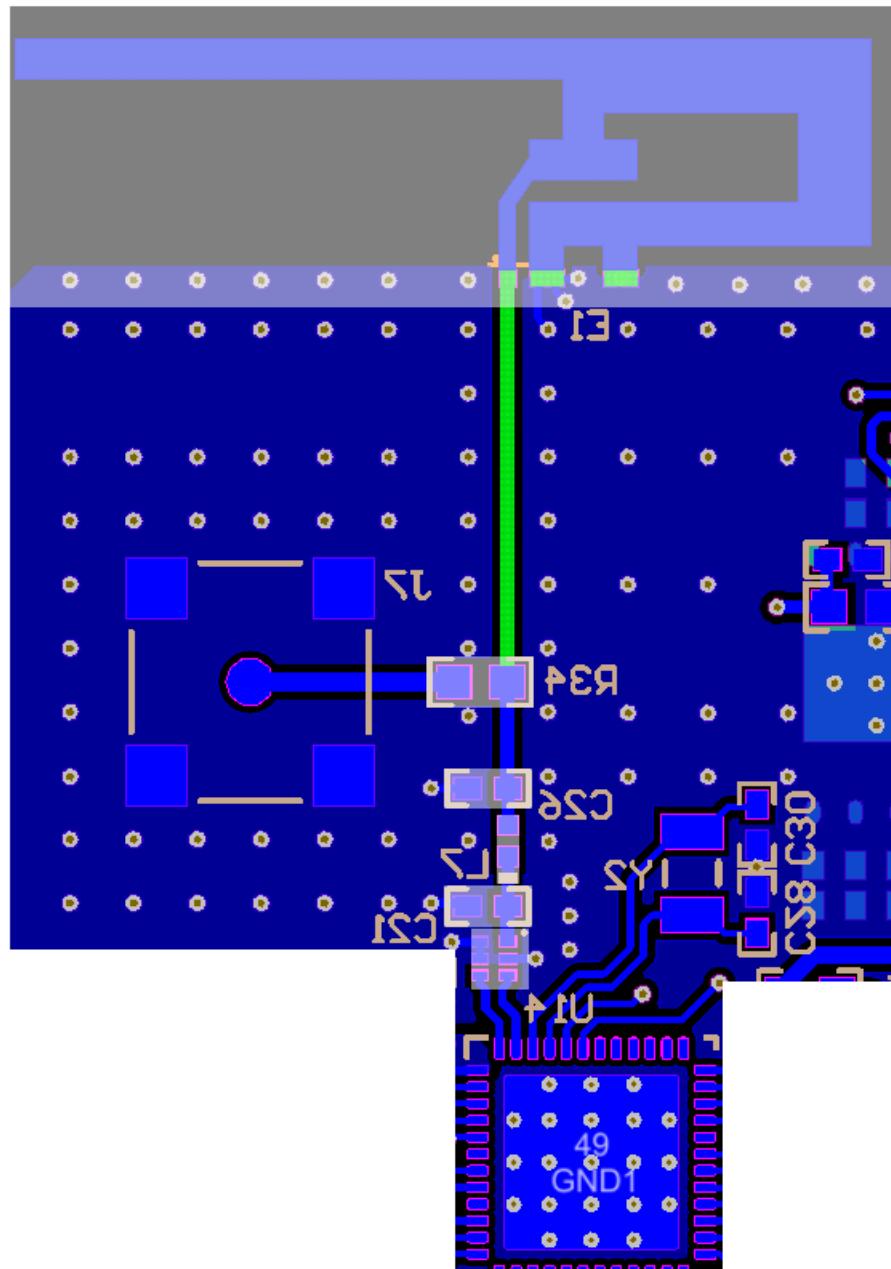
4.3.4 Connections Between BT and AFE

Figure 55. Traces Between CC2640R2F and AFE4420



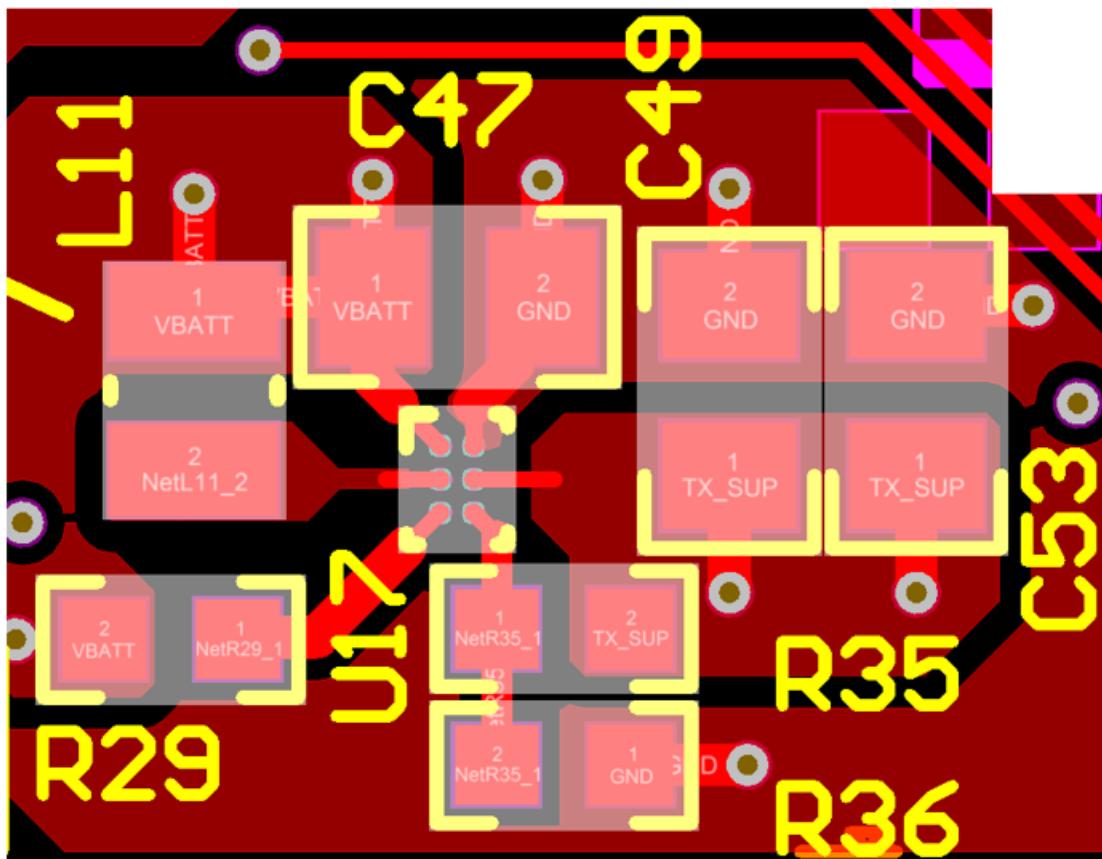
4.3.5 Connections Between BT Antenna and Chip

Figure 56. Traces Between CC2640R2F and Antenna



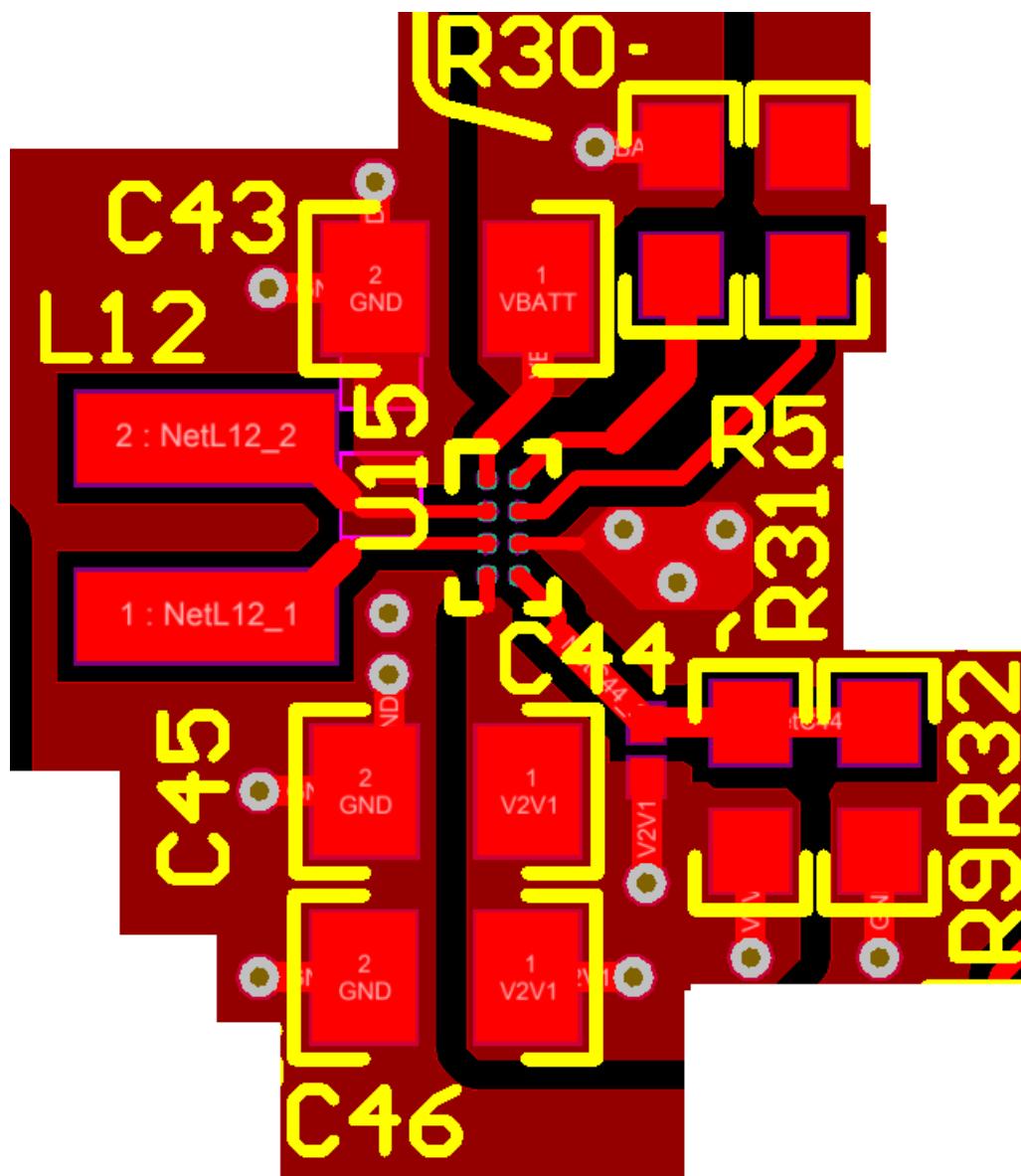
4.3.6 Boost Converter

Figure 57. Layout and Traces for Boost Converter, TPS61099



4.3.7 Buck-Boost Converter

Figure 58. Layout and Traces for Buck-Boost Converter, TPS63036



4.3.8 Layouts for PPG Sensor Boards

Figure 59. Layout for SFH 7072 Board (Top Layer)

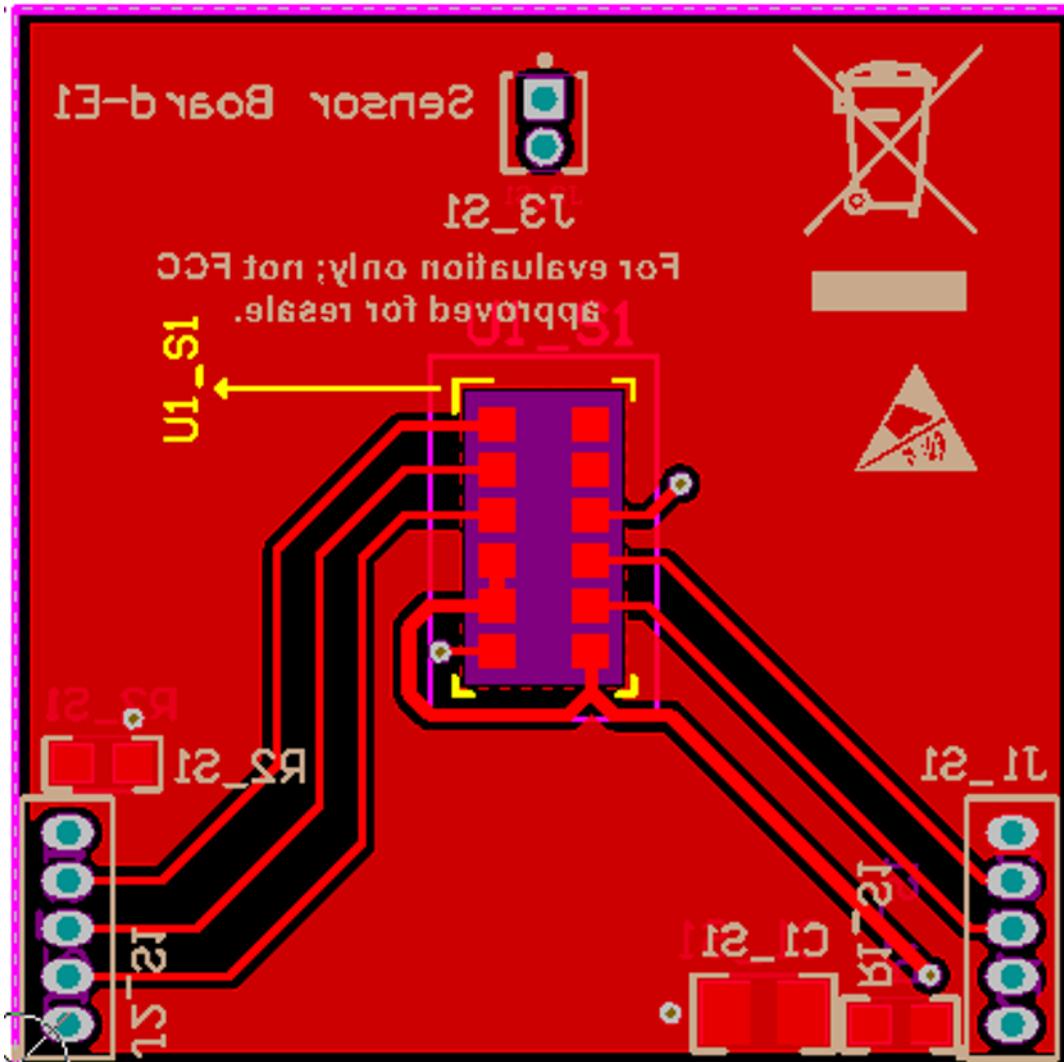
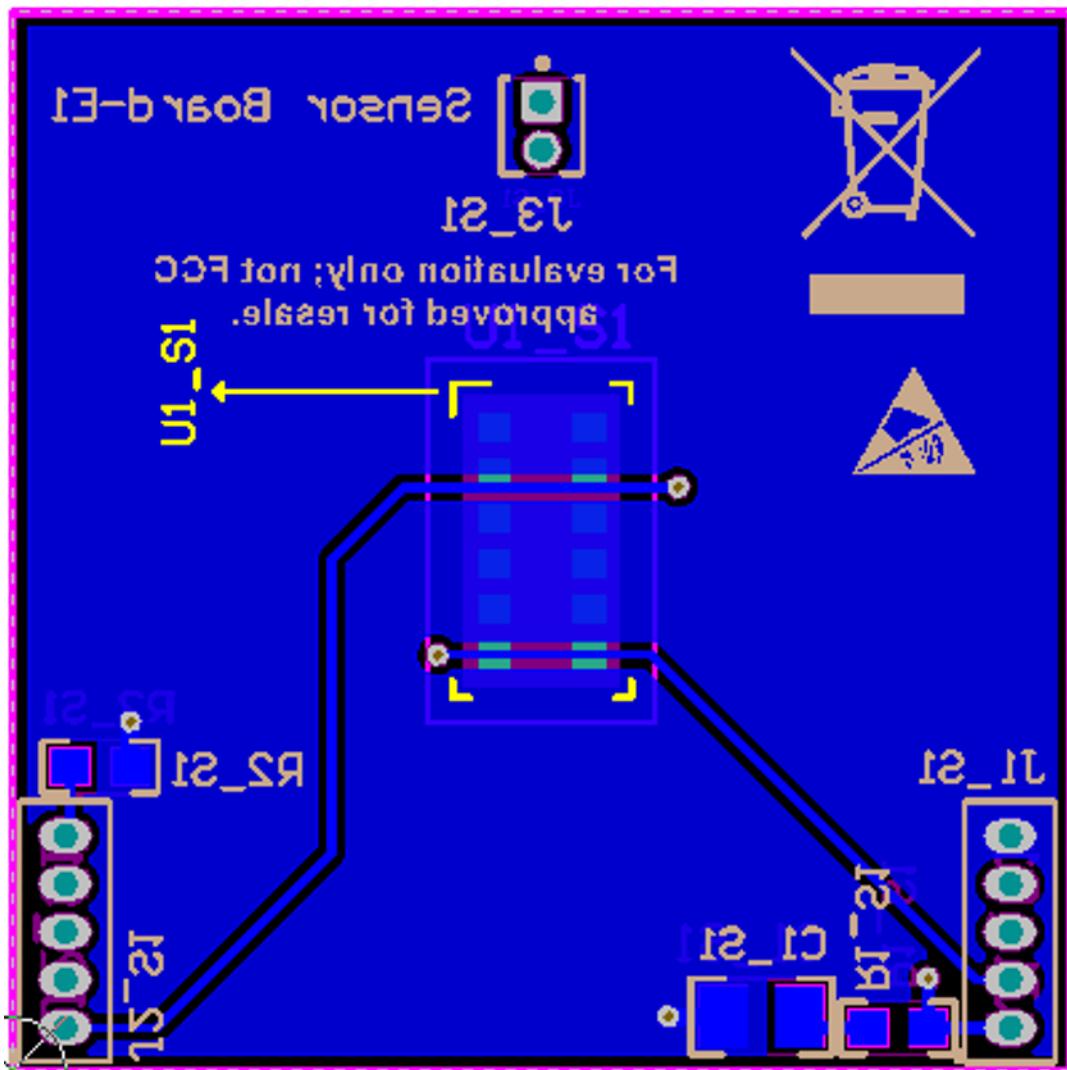


Figure 60. Layout for SFH 7072 Board (Bottom Layer)



4.3.9 Layout Prints

To download the layer plots, see the design files at [TIDA-010029](#).

4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-010029](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-010029](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-010029](#).

5 Software Files

To download the software files, see the design files at [TIDA-010029](#).

6 Related Documentation

1. Texas Instruments, [TINA-TI Simulation Software](#)
2. Texas Instruments, [Miniatrized Pulse Oximeter Reference Design Getting Started Guide](#)
3. Texas Instruments, [How to Design Peripheral Oxygen Saturation \(SpO₂\) and Optical Heart Rate Monitoring \(OHRM\) Systems Using the AFE4403](#), application report
4. Texas Instruments, [Measuring Bluetooth® Low Energy Power Consumption](#), application report
5. Texas Instruments, [Measuring Bluetooth Low Energy Power Consumption](#), application report
6. Samah Alharbi, Sijung Hu, David Mulvaney, and Panagiotis Blanos, (February 19, 2018). [An applicable approach for extracting human heart rate and oxygen saturation during physical movements using a multi-wavelength illumination optoelectronic sensor system](#). Proc. SPIE 10486, Design and Quality for Biomedical Technologies XI, 104860S; doi: 10.1117/12.2287854.

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7 About the Authors

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Revision History

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

Changes from Original (October 2018) to A Revision

Page

- | | |
|-----------------------------------|---|
| • Changed title of document | 1 |
| • Changed Description..... | 1 |

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