Design Guide: TIDA-01614

Multiparameter Front-End Reference Design for Vital Signs Patient Monitor

TEXAS INSTRUMENTS

Description

This reference design is for a multiparameter front-end of a patient monitor that measures vital sign parameters like electrocardiogram (ECG), heart rate, SpO2, and respiration. It uses biosensing front-end integrated circuits, like the AFE4403 and ADS1292R devices, to measure these parameters. It also uses three TMP117 sensors to accurately measure skin temperature. The design can interface with the pace detection module to detect the pace pulse. The design also uses an isolated UART connection to transfer data to a computer. The entire front-end subsystem runs on a rechargeable 3.7-V Lithium-ion (Li-ion) battery.

Resources

TIDA-01614	Design Folder
AFE4403	Product Folder
BQ24232	Product Folder
MSP432P4011	Product Folder
ADS1292R	Product Folder
TMP117	Product Folder
TIDA-010005	Design Folder

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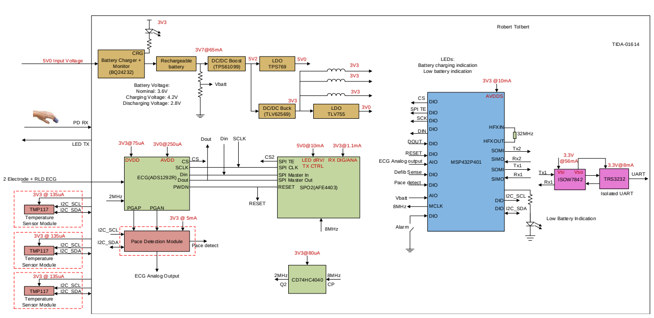
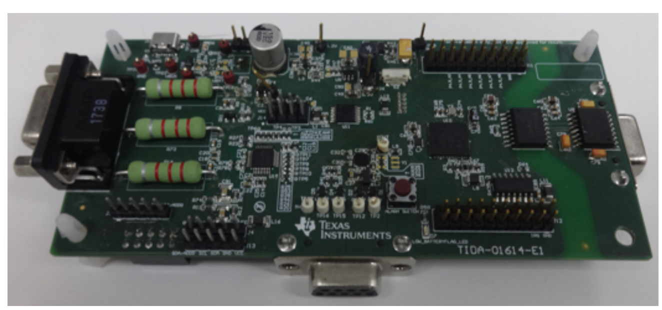
Features

- Monitors ECG, heart Rate, SpO2 %, respiration rate, and skin temperature
- Uses bio-sensing front-end AFE4403 for SPO2 and heart rate measurement and ADS1292R for ECG and respiration measurement
  - Supports up to three LEDs and three photo-diodes with ambient subtraction to improve signal-to-noise Ratio (SNR) for SPO2 and heart measurement
  - Single lead ECG Measurement with RLD
- Supports three 0.1 Celsius accurate sensors to measure the skin temperature
- Interfaces to the pace detection module (Software-configurable cardiac pacemaker detection module reference design) to enable pacemaker detection
- Enables data transfer over isolated UART interface
- Runs on a one cell Li-ion rechargeable battery

Applications

- Medical sensor patches
- Multiparameter patient monitor
- Pulse oximeter
- Electrocardiogram (ECG)





1 System Description

1.1 Introduction to Patient Monitoring System

Vital signs measure the basic body functions which help assess the general physical health of a person and give clues to identify possible disorder.

In this reference design, five primary vital signs are monitored:

- ECG
- Heart Rate
- SPO2
- Respiration rate
- Skin temperature

Using this reference design, the data is transferred using an isolated UART connection to a PC or host.

1.2 Parameters Measured Using TIDA-01614

In this reference design, five primary vital signs are measured.

ECG detects cardiac (heart) abnormalities by measuring the electrical activity generated by the heart as it contracts. ECG measurement uses ECG electrodes that are placed on the chest or at the four extremities (RA = right arm, LA = left arm, RL = right leg, LL = left leg). This reference design measures ECG with a three electrode operation, including the right leg drive, which improves CMRR. ECG is measured using TI’s bio-sensing front-end IC ADS1292R.

The ADS1292R is a low-power, multichannel, simultaneously-sampling, 24-bit deltasigma ($\Delta\Sigma$), analog-to-digital converter (ADC) with integrated programmable gain amplifiers (PGAs), internal reference, and an onboard oscillator. This device integrates various ECG-specific functions that support scalable ECG, sports, and fitness applications. The devices is used in high-performance, multichannel data acquisition systems by powering down the ECG-specific circuitry. The ADS1292R has a highly programmable multiplexer that measures temperature, supply, input short, and RLD. Additionally, the multiplexer lets you program any of the input electrodes as the patient reference drive. You can choose the PGA gain from one of seven settings (1, 2, 3, 4, 6, 8, and 12). The ADCs in the device offer data rates from 125 SPS to 8 kSPS. Communication to the device is accomplished through an SPI-compatible interface. The device provides two general-purpose I/O (GPIO) pins for general use. Multiple devices synchronize using the START pin. The internal reference is programmed to either 2.42 V or 4.033 V. The internal oscillator generates a 512-kHz clock. The versatile right leg drive (RLD) block lets you choose the average of any combination of electrodes to generate the patient drive signal.

Lead-off detection is accomplished either by an external pullup or pulldown resistor or the internal current source or sink from the device. An internal AC lead-off detection feature is available. The ADS1292R version also includes a fully-integrated respiration impedance measurement function. See the *Low-power, 2-channel, 24-bit analog front-end for biopotential measurements data sheet* for further details.

The ECG subcircuit is implemented with the ADS1292R IC. The ADS1292R is clocked either by an internal oscillator that generates a 512-kHz clock, or externally through the CLK pin (pin 17). Each clocking method has its advantages and disadvantages. Although the external clock provides high accuracy, it requires additional external components. However, the internal clock requires fewer components, but it suffers from temperature-dependent performance. As mentioned in the data sheet, internal clocking is ideal for low-power, battery-operated systems. The internal oscillator is trimmed for accuracy at room temperature. The accuracy varies over the specified temperature range. The only permissible external clock frequencies are 512 kHz or 2.048 MHz. The higher frequency option helps the SPI run at a higher speed. The ADS1292R uses the SPI communication interface to communicate with a Microcontroller (MCU), MPU, or DSP.

1.3 SPO2 Monitoring

Oxygen binds to hemoglobin in red blood cells as it moves through the lungs. It travels throughout the body as arterial blood. A pulse oximeter uses two light frequencies (red and infrared) to determine what percentage of hemoglobin is saturated with oxygen. The percentage is called blood oxygen saturation, or SpO2. It is the percentage of oxygenated hemoglobin (hemoglobin containing oxygen) compared to the total amount of hemoglobin in the blood (oxygenated and non-oxygenated hemoglobin). A pulse oximeter also measures and displays the pulse rate and the SpO2 level simultaneously. The signal obtained from the pulse oximeter is the photoplethysmographic (PPG) signal, which shows the blood flow at the extremities. SpO2 is measured by a pulse oximeter, which is an indirect, non-invasive method. It emits and absorbs a light wave passing through blood vessels (or capillaries) in the fingertip. A variation of the light wave passing through the finger gives the SpO2 measurement since the degree of oxygen saturation causes variations in the blood's color. This value is represented by a percentage. If your pulse oximeter says 98%, then each red blood cell is made up of 98% oxygenated hemoglobin and 2% non-oxygenated hemoglobin. Normal SpO2 values vary between 95% and 100%. Anything lower than 90% may be a cause for concern.

Red and infrared (IR) lights are used to estimate the true hemoglobin oxygen saturation of arterial blood. Oxyhemoglobin (HbO2) absorbs visible and infrared IR 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 known as the perfusion index percentage.

Equation 1 shows how to approximate the ratio of ratios and R:

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

Equation 2 shows the standard model for computing SpO2:

$$\%\ \text{SpO2} = 110 - (25 \times R) \quad (2)$$

This model is often used in medical devices literature. However, accurate % SpO2 is computed based on the empirical calibration of the ratio of ratios for the specific device.

1.4 Pace Detection

The TIDA-01614 can be interfaced to TI's pace detection module (TIDA-010005) to identify a pacemaker pulse in the ECG waveform. It detects the pace with rise time of (30 µs–200 µs), amplitude of (8 mV–700 mV), and duration of (100 µs–2000 µs).

2 Key System Specifications

Table 1 lists the different characteristics and specifications of the TIDA-01614 board.

Table 1. Key System Specifications

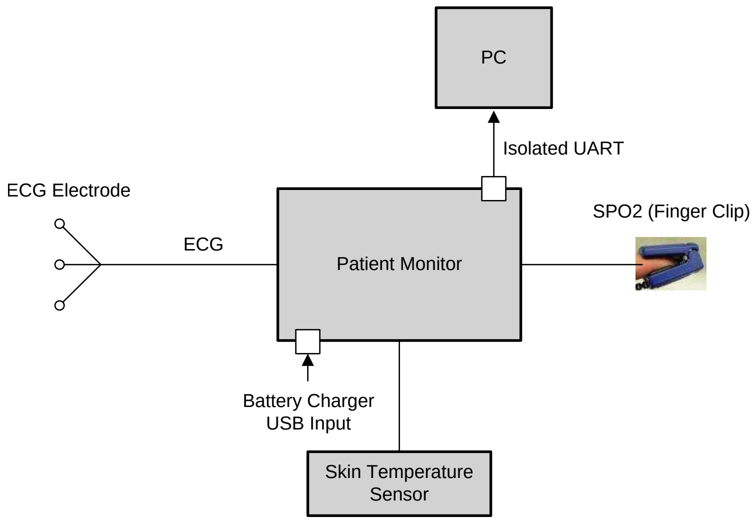
CHARACTERISTICS	SPECIFICATIONS
ECG	One lead ECG operation with RLD. Sampling rate of 500 samples per second, supports ECG sensitivity of 100 µV
SPO2 Measurement	Works in transmissive SPO2, refresh rate of 500 Hz
Skin Temperature Measurement	Three temperature sensor with 0.1 degree accuracy
Pace pulse Rise-time (TR) measurement range	30–200 µs
Pace pulse duration (TD) measurement range	0.1–2 ms
Input Pace signal amplitude range	8 mV–700 mV
Input Voltage (Vin)	5 V from Micro-USB

3 System Overview

3.1 High-Level System Description

Typically patient monitors are connected to the body so they can measure multiple parameters of the body. Figure 1 shows a high-level block diagram of such a system. The system connects to the PC through a wired, isolated UART connection.

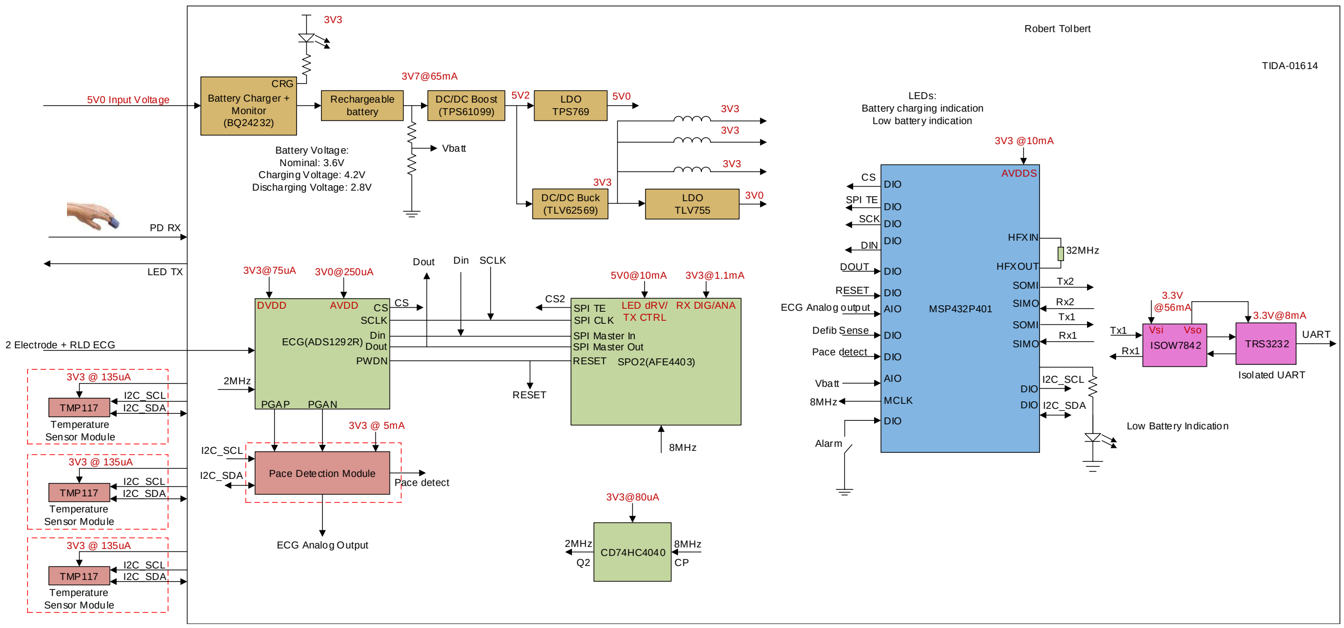
Figure 1. System Level Block Diagram



3.2 Block Diagram

Figure 2 shows the TIDA-01614 block diagram.

Figure 2. TIDA-01614 Block Diagram



This design measures ECG, Respiration, SpO2, heart rate, and skin temperature. ECG and respiration are measured using the IC ADS1292R with standard wet ECG electrodes. The SpO2 and heart rate are measured using the IC AFE4403 and the standard transmissive type finger clip. Skin temperature is measured with TMP117 temperature sensors. The TIDA-010005 (Software-configurable cardiac pacemaker detection module reference design) is interfaced to this reference design to detect the presence of pace pulse and to read the pace pulse parameters.

The whole system runs with a 3.7-V rechargeable Li-ion battery. This design uses a TPS61099 boost regulator to convert the battery from 3.7 V to 5.2 V. The LDO TPS76901 generates a 5-V output with an input voltage of 5.2 V. 3.3 V is generated using the buck converter TLV62569 with an input voltage of 5.2 V. A value of 3 V is generated using the LDO TLV75530 with an input voltage of 3.3 V. This reference design uses an isolated UART connection with the ISOW7821 digital isolator and TRS3232 transceiver.

3.3 Design Considerations

This section provides the design details for the monitoring system.

3.3.1 ECG and Respiration Circuit

Figure 3 shows the schematic of the ECG subcircuit and the nets of ADS1292_ERA, ADS1292_ELA, and ADS1292_RLD and corresponds to the probes. The more channels an ECG monitoring system has, the better the ECG signal can be analyzed. ADS1292R is equipped with only two channels. Figure 4 shows that Channel 1 is used for respiration rate calculation and Channel 2 is used for ECG measurement. The frequency from the ECG signals can range from 0.01–300 Hz. ECG drift occurs when the ECG signals drift all over the monitoring device. Current injection and resistor biasing reduce ECG drift, but for added security, the ECG subcircuit uses both methods. Figure 4 shows resistors R21, R22, R24, R10, and capacitor C16, which form the RLD current injection method. Figure 3 shows resistors R15, R17, R54, and R72, which form the resistor biasing method. Figure 5 shows the ADS1292 decoupling capacitors.

The ADS1292R is a two-channel device, but if respiration rate detection is enabled, then Channel 1 can no longer measure ECG signals. Four pins are needed to detect the respiration rate:

- IN1P
- IN1N
- RESP_MODP
- RESP_MODN

The ECG subcircuit can only measure ECG signals, but you can extract the ECG signal respiration rate with mathematical manipulation.

Figure 3. ECG Subcircuit - Leads

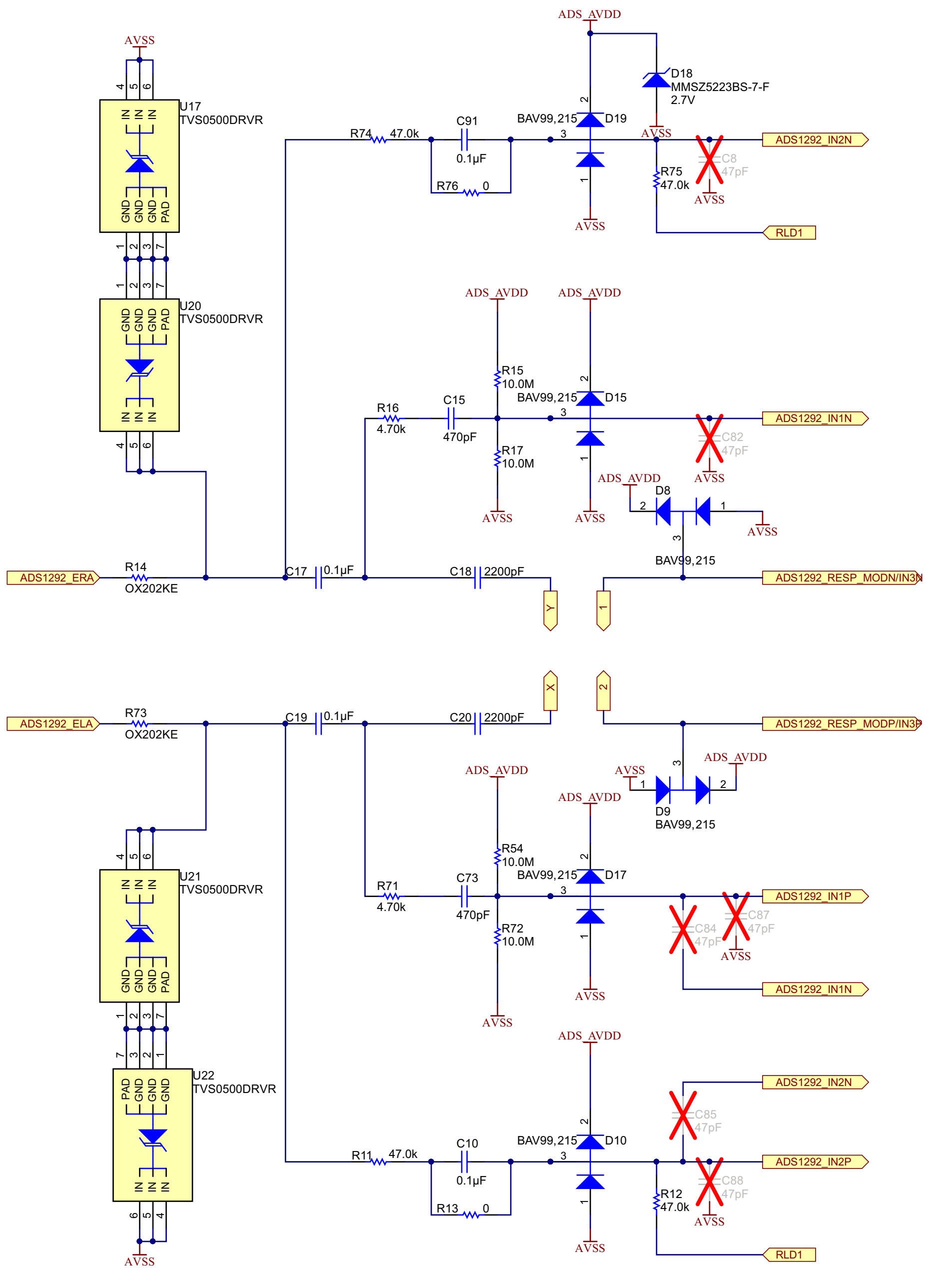


Figure 4. ECG Subcircuits – ADS1292R and RLD

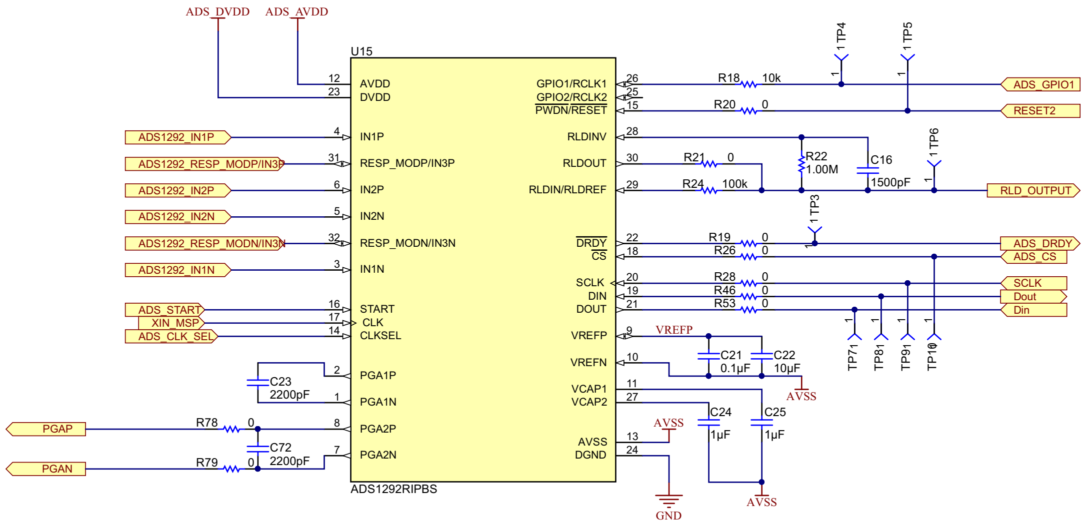


Figure 5. ECG Subcircuit – Decoupling Capacitor and Ferrite Bead

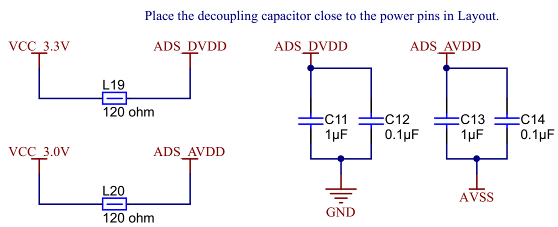
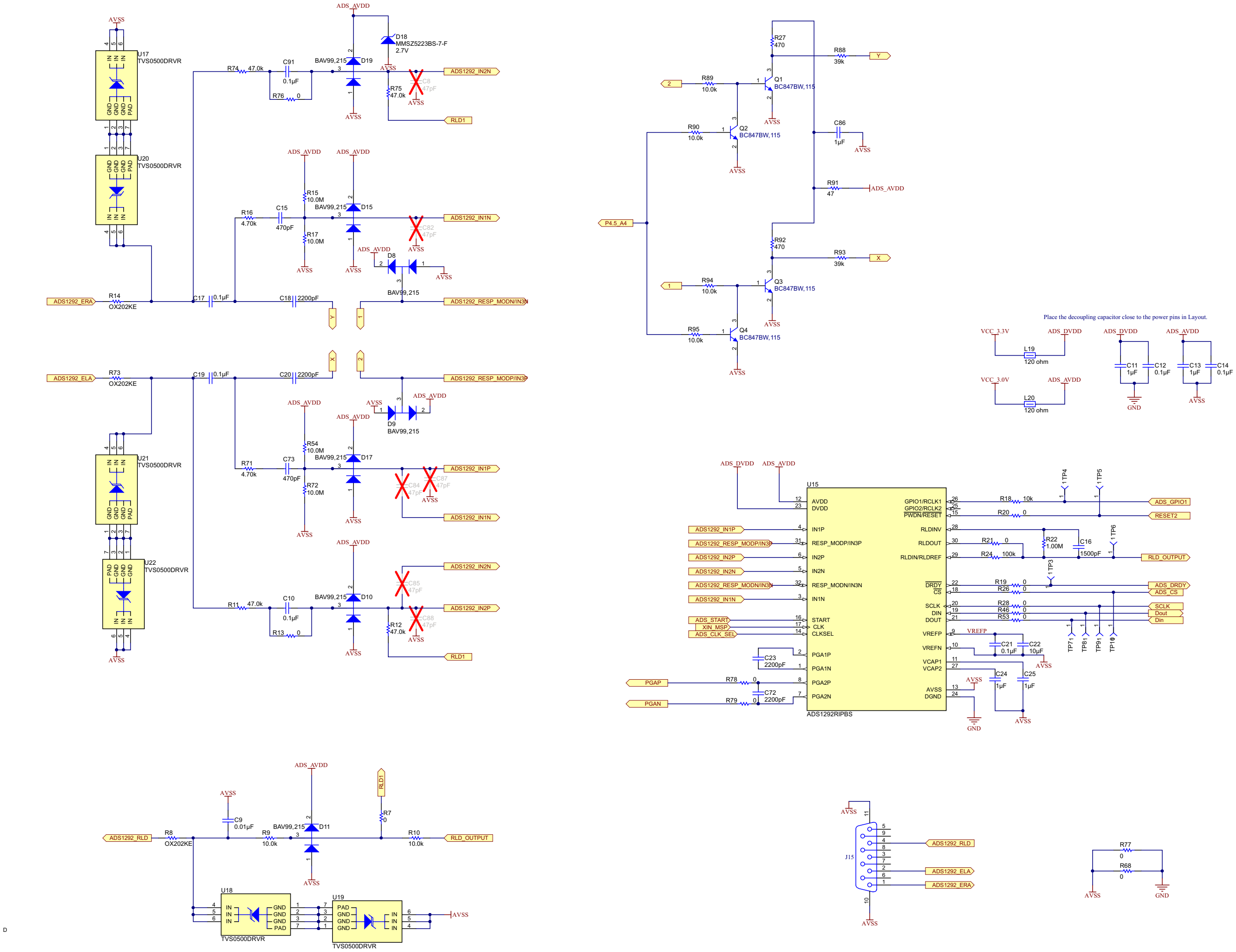


Figure 3 shows diodes D19, D15, D8, D17, D9, D10, and D11. These diodes limit the voltage that appears on the ADS1292R pins. Figure 3 shows optional TVS diodes U17, U20, U21, U22, U18, and U19. These diodes protect the circuitry against excess voltage.

The PGAP and PGAN pins extract pace pulse present in the ECG signal. These signals are given to the J9 connector, which connect to the pace pulse detection module. See reference design TIDA-010005 for the pacemaker detection circuit. You can conduct a test by connecting the TIDA-010005 board. See Section 4.2 for the test results.

Figure 6 shows a two electrode mode of operation where the ADS1292_ERA and ADS1292_ELA electrodes are connected. To improve the CMRR in this mode, R7 is populated. The RLD_OUTPUT of the IC and the resistive divider form with R75 and R74 to generate equal and opposite voltage, cancelling out the CM voltage at the pin ADS1292_IN2N. Similarly, R12 and R11 form a resistive divider and cancel out the CM voltage at the input of the IC pin ADS1292_IN2P.

Figure 6. ADS1292_ERA and ADS1292_ELA – Two-Electrode Operation



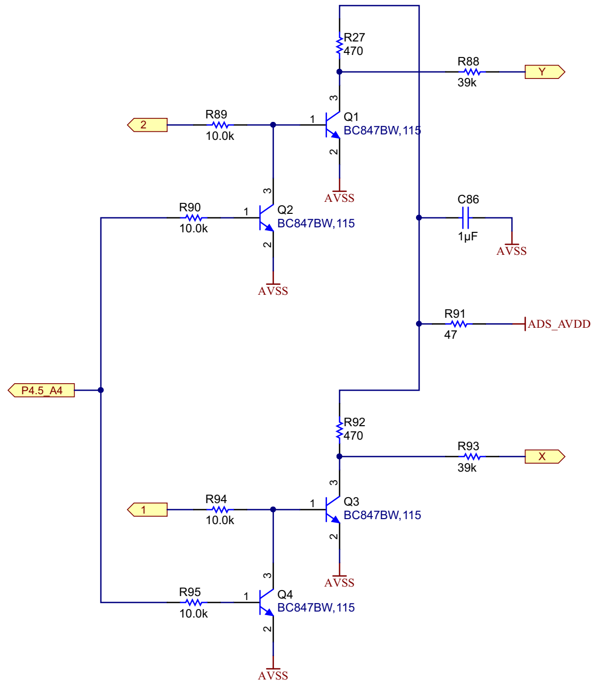
In the three electrode mode of operation, disconnect R7 and the RLD amplifier to create an equal and opposite signal, cancelling out the 50 or 60 HZ common mode signal coming from the body and improving the CMRR.

A 32-kHz or 64-kHz signal is sent through the R23 and R27 resistor to the right and left electrode. The R23 and R27 resistors form a resistive divider and the body impedance of 500 Ω, which varies from 0.1 Ω to 1 Ω with respiration. The high-frequency envelope, modulated by the variation in the impedance of the body, is fed differently through the R16 and R71 to the IC through ADS1292_IN1P and ADS1292_IN1N. Then, the envelope is demodulated and digitized to form the respiration. In this design, ADS1292R runs with an internal clock of 512 kHz.

For the ECG monitoring to be effective, the recorded ECG signals must be clean and free of noise. Any distortion of the ECG signals from improper electrode-to-patient placement can lead to improper or missed diagnosis. Use monitoring techniques to verify that electrodes are properly adhered to the patient. The ADS1292R offers lead-off detection, which is a built-in monitoring circuitry that constantly monitors the ECG leads to ensure they are properly adhered to the patient’s skin. With the ADS1292R, lead-off detection is implemented either by using an external pullup or pulldown resistor, or the device internal current source or sink. An internal AC lead-off detection feature is also available. You do not need external circuitry to enable lead-off detection.

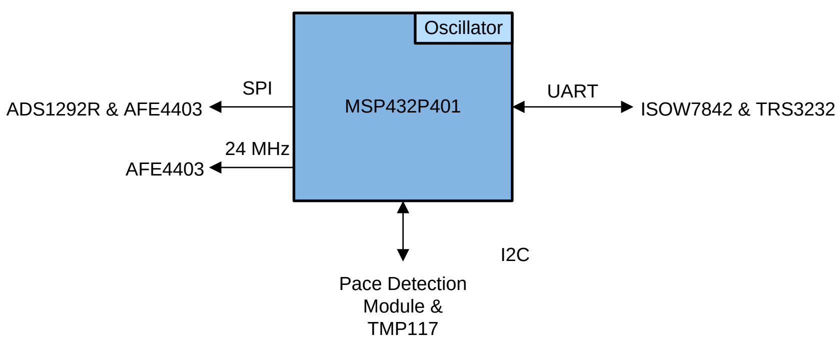
Figure 5 shows that decoupling capacitors C11, C12, C13, C14, and ferrite bead L19 and L20 have sufficient suppression to switch the noise from the 3.3 V switching power supply. Figure 10 shows that the respiration is switched off every 30 seconds, but the transistor switch keeps the pacemaker on.

Figure 7. Electronic Switch



3.3.2 MSP432P401V

Figure 8. MCU Connections



This reference design uses the MSP432P401 microcontroller. Figure 8 shows SPI, UART, and I2C communicating to the devices. ADS1292R and AFE4403 are interfaced by SPI. It is interfaced to PC using the UART interface. The pace detection module and temperature sensor communicates through the I2C. The microcontroller runs with the internal oscillator of 48 MHz. 24 MHz of the HSM clock is given from the microcontroller to the AFE4403. Battery voltage is given to the IO pin of the microcontroller to indicate low battery voltage.

3.3.3 Timing Diagram

Figure 9 shows ADS1292R and AFE4403 Read and UART transmission (AFE4403 RDY comes after ADS1292R read).

Figure 9. Timing Diagram – Case 1

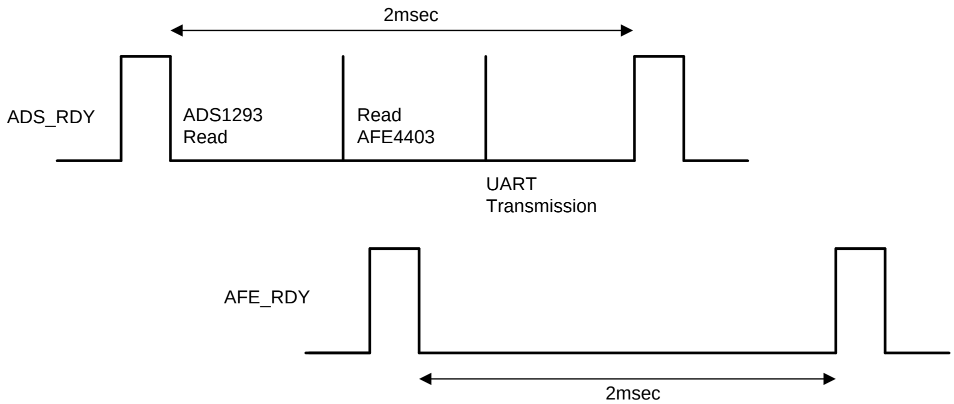
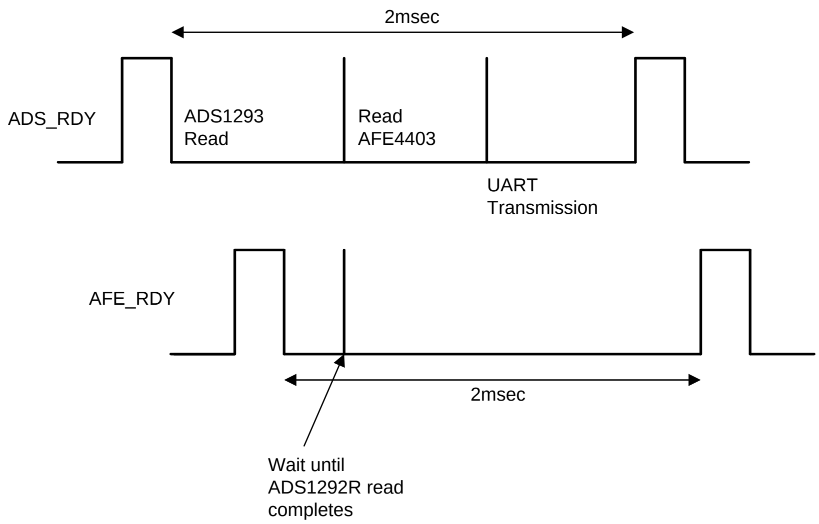


Figure 10 shows ADS1292R and AFE4403 Read and UART transmission (AFE4403 RDY comes while reading ADS1292).

Figure 10. Timing Diagram – Case 2



Read the temperature sensor every two seconds. Respiration is switched off and pacemaker is ON every 30 seconds.

3.3.4 SPO2 Measurement

In this reference design, SPO2 is measured using the TI bio-sensing analog front-end IC AFE4403. Figure 11 shows different connections for the AFE4403 device. The AFE4403 devices needs following power supplies:

- RX_ANA_SUP (3.3 V)
- RX_DIG_SUP (3.3 V)
- LED_DRV_SUP (5 V)
- TX_CTRL_SUP (5 V)

RX_ANA_SUP (3.3 V) and RX_DIG_SUP (3.3 V) are generated using the U5 IC. The L9 and L10 ferrite beads are used to suppress the switching noise from 3.3 V switching power supply. LED_DRV_SUP (5 V) and TX_CTRL_SUP (5 V) are generated using the LDO U4.

For PPG measurement, the LEDS are driven using the TXP. The TXN is used for the red LED and the IR LED and TX_LED_3 (TX_LED_3 is not used in this design) is used for the green LED. The reflected signals are detected using PDs connected to the INP and INN. The BG pin is connected to the internal bandgap voltage and is decoupled using 2.2 µF.

Figure 11. AFE4403 Connection Schematic

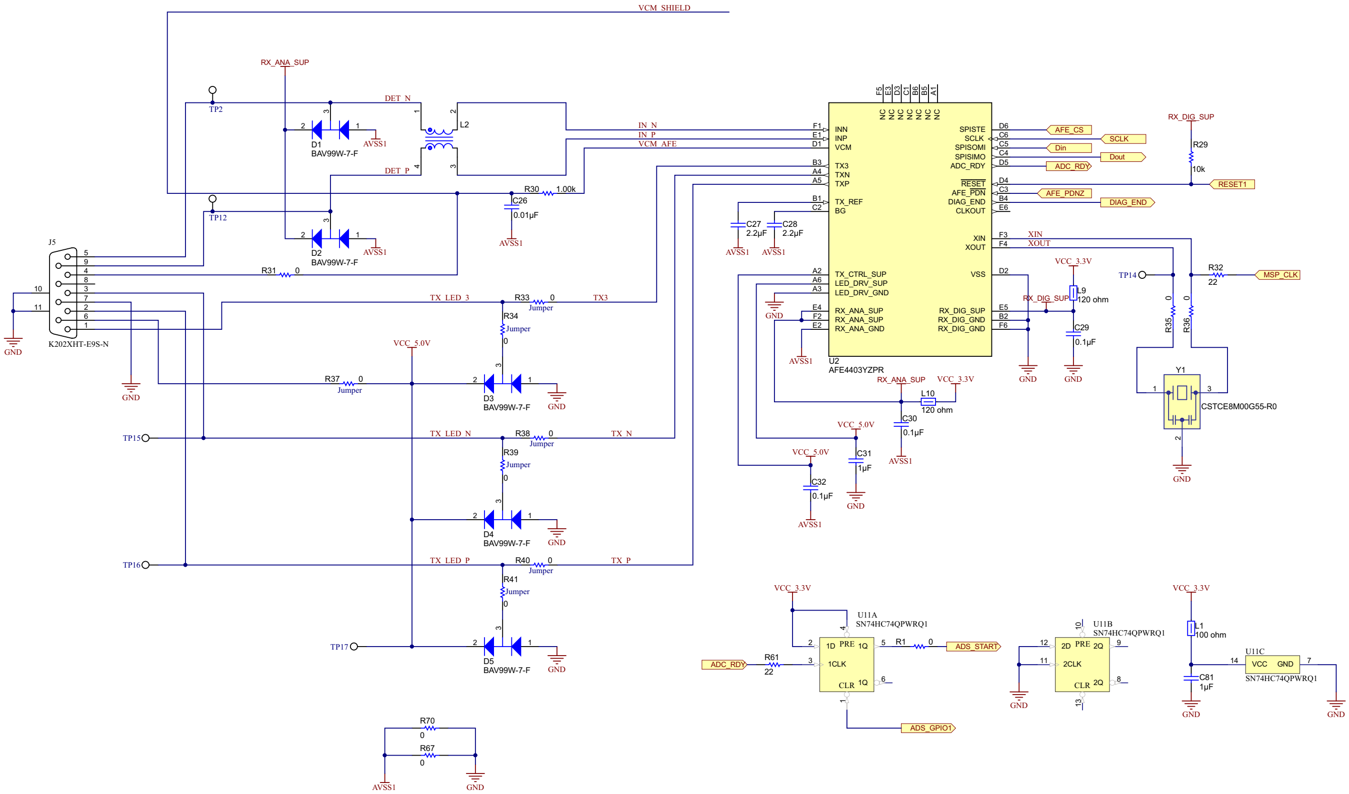


Table 2 lists the connections between the AFE4403 and the MSP432P401V device.

Table 2. Connections Between the AFE4403 and MSP432P401V Device

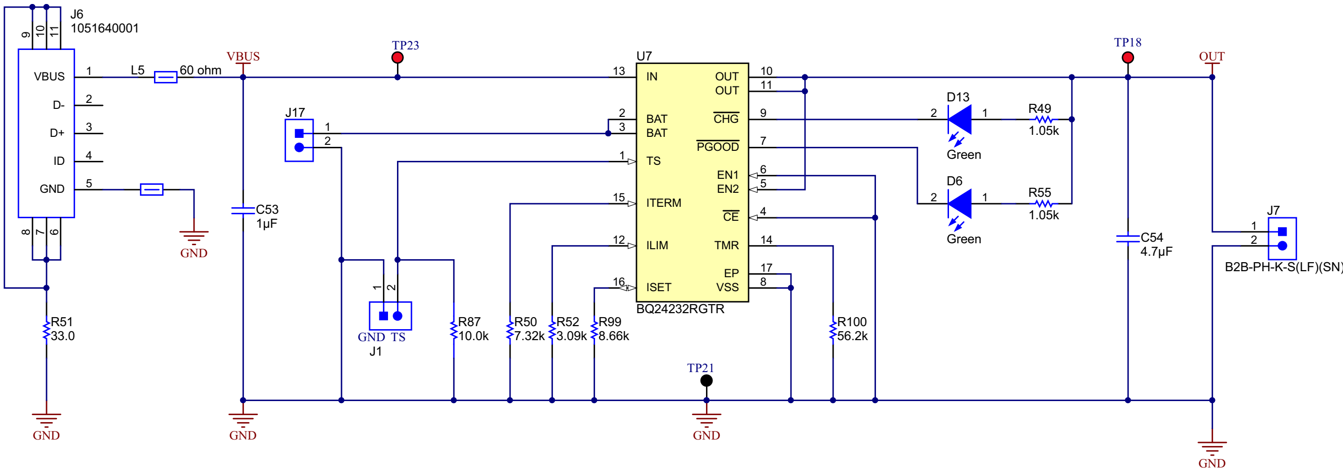
AFE4403 PIN NUMBER	FUNCTION	MSP432P401V PIN NUMBER	FUNCTION	COMMENTS
F3	XIN	35	P4.4/HSMCLK/SVMHOUT/A9	AFE Clock
B4	DIAG_END	7	P1.6/UCB0SIMO/UCB0SDA	Output signal that indicates completion of diagnostics
C3	AFE_PDN	20	P3.1/PM_UCA2CLK/	AFE-only power-down input
D4	RESET1	19	P3.0/PM_UCA2STE	Reset for the AFE
D5	ADC_RDY	13	P2./PM_UCA1STE	ADC Ready Signal
C4	Dout	4	P1.3/UCA0TXD/UCA0SIMO	SPI_OUT
C5	Din	3	P1.2/UCA0RXD/UCA0SOMI	SPI_IN
C6	SCLK	2	P1.1/UCA0CLK	SPI Clock
D6	AFE_CS	5	P1.4/UCB0STE	AFE chip select

AFE4403 works with an external clock. 24 MHz HSMCLK from MSP432P401 is given to the AFE4404, which is internally divided by six to have 4 MHz for the AFE4403 ADC.

The SPO2 finger clip is connected to the J5 connector. The transmit section integrates the LED driver and the LED current control section with an 8-bit resolution. The RED and IR LED reference currents can be independently set. The driver works in H-Bridge configuration works in transmissive manner. The front-end receiver consists of a differential current-to-voltage (I-V) transimpedance amplifier (TIA) that converts the input photodiode current into an appropriate voltage. The feedback resistor of the amplifier is programmable to support a wide range of photodiode currents. Next to the TIA is an Amb cancellation DAC, Filtering stage, Buffer, and an ADC. See the *AFE4403 ultra-small, integrated analog front-end for heart rate monitors and low-cost pulse oximeters data sheet* for more details. The D1 to D5 diodes limit the voltage that appear on the pins of the IC.

3.3.5 Li Ion Battery Charger

Figure 12. Li-Ion Battery Charger Using BQ24232



The following list provides details about the design:

- Supply Voltage = 5 V
- Charging current = 0.1 A
- Input current limit, ILIM = 500 mA
- Termination current = 25 mA
- Safety timer duration, Fast charge = 7.5 hours
- Battery temperature sense = 10 KΩ NTC (103AT-2)

How the fast charge current (ISET) is set:

- RISET = [K(ISET) / ICHG]
- K(SET) = 870 AΩ
- RISET = R99 = [870 AΩ / 0.1 A] = 8.7 kΩ

How the input current limit (ILIM) is set:

- RLIM = KILIM / I1-MAX
- KILIM = 1530 AΩ
- RILIM = 1530 AΩ / 0.5A = 3.06 kΩ

How the termination current threshold (ITERM, BQ24232) is set:

- RITERM = RISET × ITERM × KITERM
- KITERM = 0.03 A
- RITERM = 8.7 kΩ × 0.025 A / 0.03 A = 7.25 kΩ

How the 7.5-hour fast-charge safety timer is set:

- RTMR = tma × CHG
- KTMR = 48 s / kΩ
- RTMR = (7.5 hr × 3600 s/hr) / (10 × 48 s/kΩ) = 56.25 kΩ

If you are using a Li-ion battery, place a thermistor close to the battery and connect it to the Ts pin of the charger for protection. If the temperature gets too high while it is charging, the thermistor turns off. In this reference design, Connector J1 connects SEMITEC 103-AT-2 temperature sensor from the battery pack to the Ts pin of the IC. See the *USB-friendly lithium-ion batttery charger and power-path management IC data sheet* and *bq24072/3/4/5/9(T) and bq24230/21.5-A single-chip li-ion and li-polymer charge management IC EVM user's guide* for detailed design instructions and recommendations. See TI's WEBENCH® Design Center to generate a solution with this part.

This reference design uses a 3.7-V Li-Ion battery. The board consumes 120 mA, so the battery runs continuously for 4.16 hours.

3.3.6 3-V Generation Using LDO

Figure 13. 3-V Generation Using TLV5530

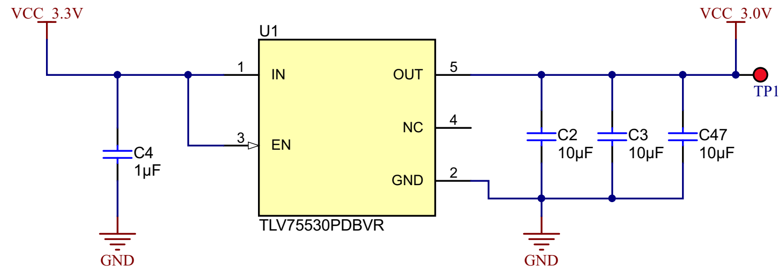


Figure 13 shows the LDO circuit generating 3 V from a 3.3-V input with the TLV75530. This is a fixed output LDO. This reference design uses a 500-mAh 3.7-V Li-ion battery. The board consumes 120 mA, so the battery runs for 4.16 hours continuously. This circuit provides 60 mAs of current. This 3 V provides supply to the ADS1292R ADS_AVDD supply. The TLV755P device is a 500-mA low-IQ small-size low-dropout regulator, with an input voltage range of 1.45 V to 5.5 V. The device is offered in fixed output voltages ranging from 0.6 V to 5 V. See the *Low-voltage, low-noise power supply reference design for ultrasound analog front end reference design* and the *TLV755P 500-mA, low I_Q, small size, low dropout regulator datasheet* for detailed design instructions and recommendations. See *TI's WEBENCH® Design Center* to generate a solution with this part.

3.3.7 5-V Generation Using LDO

Figure 14. 5-V Generation Using TPS76901

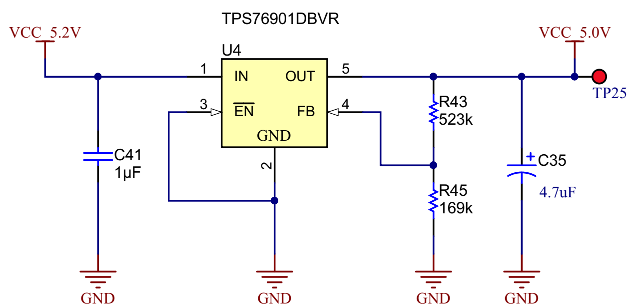


Figure 14 shows the LDO circuit generating 5 V from a 5.2-V input using the TPS76901. The 5 V provides the LED_DRV_SUP and TX_CTRL_SUP of the AFE4403 IC. The TPS76901 device is an ultra-low power 100-mA low-dropout linear regulator.

Output Voltage Set

Figure 14 shows the output voltage from the TPS76901 adjustable regulator being programmed with an external resistor. Equation 3 shows how to calculate the output voltage.

$$V_{OUT} = V_{REF} \times \frac{R_1 + R_2}{R_2}$$

where

- R1 = R43 and R2 = R45
- VREF = 1.16 V typ (the internal reference voltage) (3)

Gives Vo = 5 V, with R43 = 523 kΩ, R45 = 169 kΩ and Vref = 1.16.

See the *Ultra-low-power 100-mA low dropout linear regulator data sheet* for detailed design instructions and recommendations. See *TI's WEBENCH® Design Center* to generate a solution using this part.

3.3.8 5.2-V Generation Using DC/DC Converter

Figure 15. 5.2-V Generation Using DC/DC Converter

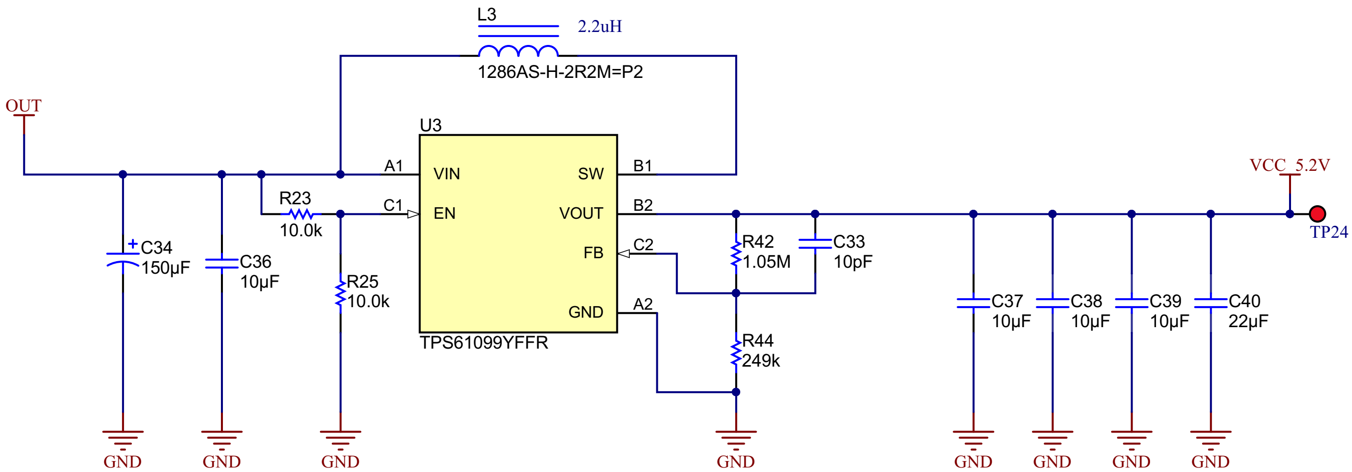


Figure 15 shows the switching circuit generating 5.2 V using the TPS61099 from the battery voltage, VBAT. Nominal value of VBAT is 3.7 V, but this varies between 2.8 V and 4.2 V. This 5.2-V boost converter is used as input to the LDO TPS76901 to generate 5 V for the LED_DRV_SUP and TX_CTRL_SUP of the AFE4403 IC. This 5.2 V is the input to the TLV62569, a 3.3-V generating DC/DC converter. This converter operates with a switching frequency of 400 kHz. See the *TPS61099x synchronous boost converter with ultra-low quiscent current data sheet* for detailed design information. The TPS61099 device is a Synchronous Boost Converter with Ultra-Low Quiescent Current.

Output Voltage Set

The resistor divider network of R42 and R44 sets the output voltage. The reference voltage, VREF, is 1 V. Equation 4 helps you calculate the output voltage.

$$V_{OUT} = V_{FB} \times \left[1 + \frac{R_1}{R_2}\right] = 0.6\ V \times \left[1 + \frac{R_1}{R_2}\right]$$

where

- R1 = R42 and R2 = R44 and VREF = 1 V (4)

Substituting R42, R44, and VREF in Equation 4 gives you V_{OUT} = 5.2 V.

See the *TPS61099x synchronous boost converter with ultra-low quiscent current data sheet* and *TPS61099 evaluation module user's guide* for detailed design instructions and recommendations. See *TI's WEBENCH® Design Center* to generate a solution using this part.

3.3.9 3.3-V Generation Using DC - DC Converter

Figure 16. 3.3-V Generation Using DC - DC Converter

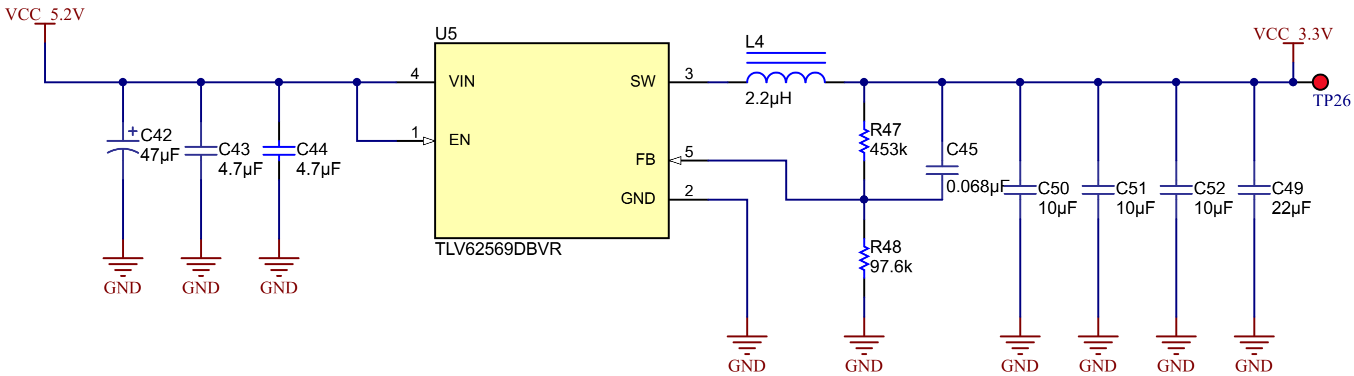


Figure 16 shows the switching circuit generating 3.3 V using the TLV62569 from the 5.2-V DC/DC Converter. 3.3 V is provided to the following:

- The MCU
- The RX_DIG_SUP and RX_ANA_SUP supply of the AFE4403
- The ADS DVDD of ADS1292R

This 3.3 V is the input to the 3 V-generating LDO TLV75530. Ferrite beads are used at each input to avoid switching noise from the 3.3 V converter. This is designed to operate with a switching frequency of 400 kHz. The TLV62569 2-A is a high efficiency synchronous buck converter in the SOT Package. See the *TLV62569 2-A high efficiency synchronous buck converter in SOT package data sheet* and *TLV62568EVM-789 and TLV62569EVM-789 evaluation modules user's guide* for detailed design information.

Output Voltage Set

Equation 5 shows an external resistor divider setting the output voltage.

$$V_{OUT} = V_{FB} \times \left[1 + \frac{R_1}{R_2}\right] = 0.6\text{ V} \times \left[1 + \frac{R_1}{R_2}\right]$$

where

- R1 = R47, R2 = R48 and VFB = 0.6 V (5)

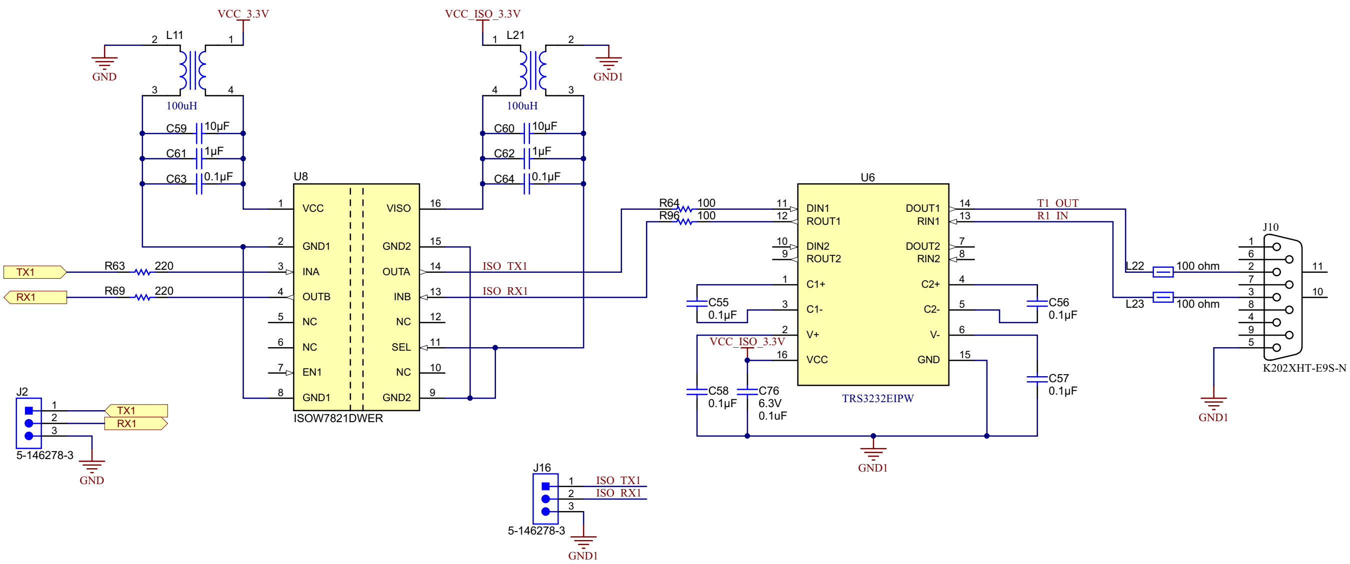
Substituting R47, R48, and VFB in Equation 5 gives you Vout = 3.3 V.

See the *Ultralow-power 100-mA low dropout linear regulator data sheet* and *TLV62568EVM-789 and TLV62569EVM-789 evaluation modules user's guide* for detailed design information.

3.3.10 Isolated UART

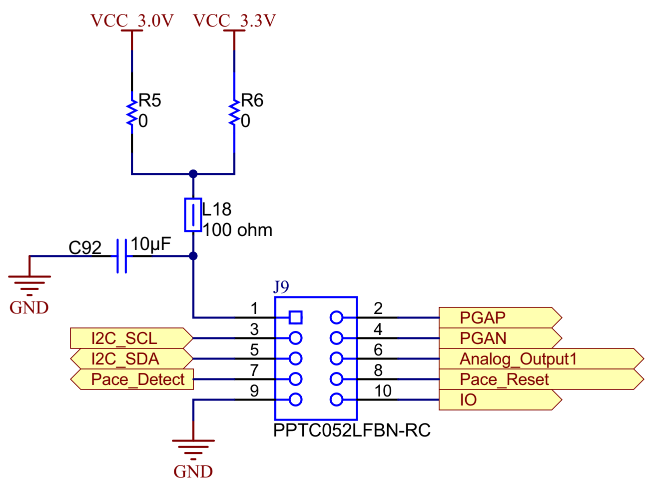
This reference design provides an isolated UART connection for the wired environment. The U8 IC ISOW7821DWER is the isolator and U9, TRS3232DWR, is the UART transceiver. The J16 connector connects to the PC with an isolated UART if the voltage is 3.3 V. The J2 connector provides the UART RX1 and TX1 without isolation. The J16 connector provides an isolated UART TX and RX.

Figure 17. Isolated UART Circuit



3.3.11 Other Interfaces

Figure 18. Pace Detect Module Connector



J9 represents the connection to the pace detection module (TIDA-010005). The pace detection module is interfaced from the I2C to the main TIDA board. PGAP and PGAN from ADS1292R IC of the TIDA-01614 board goes to the pace detection module and detects if any pace pulse is present in the ECG waveform and gives a pace detect to the MCU. Pace reset resets all the counters on the TIDA-010005 board.

Figure 19. Temperature Connector Sensor

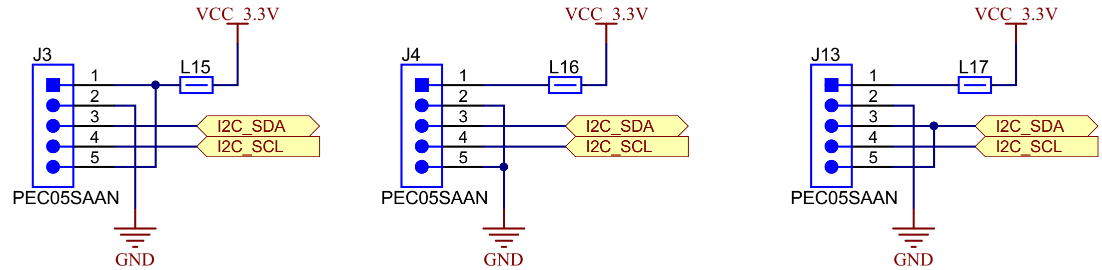


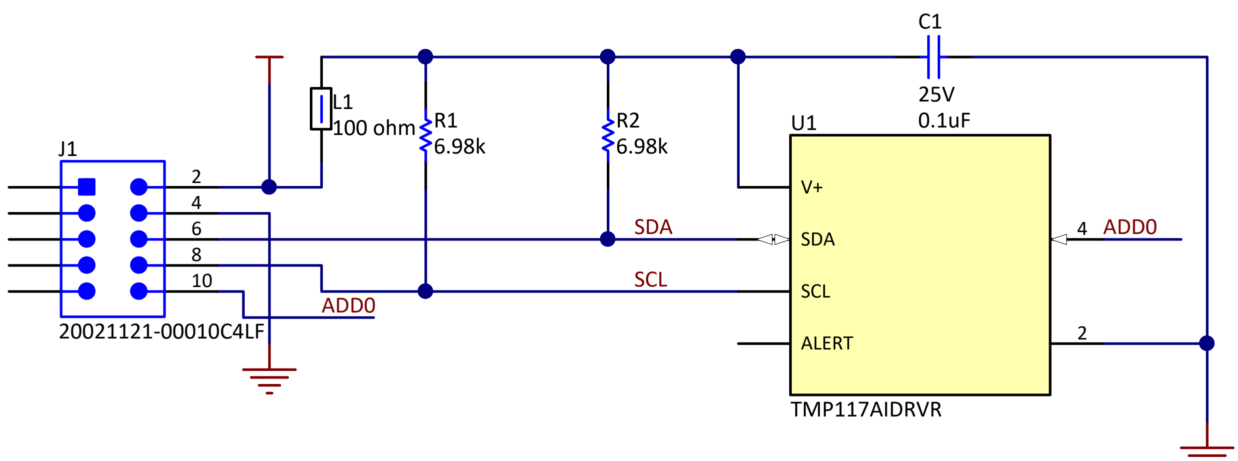
Figure 19 shows the connection to the temperature sensor TMP117. Three TMP117 temperature sensors are used for accurate measurement. Interface is from the I2C to the MCU. ADD0 pin is the fifth pin and connects to GND, V1, and SDA lines to select the unique slave address.

3.3.12 Temperature Sensor Board

Figure 20 shows the temperature sensor circuit. The TMP117 is a low-power, high-precision temperature sensor that provides a 16-bit temperature result, with a resolution of 7.8125 m°C, and an accuracy up to ±0.1°C with no calibration. The TMP117 operates from 1.8 V to 5.5 V, usually consuming 3.5 µA, and comes in a 2.00 mm × 2.00 mm WSON package. The device also features integrated EEPROM. Three such boards are interfaced to the main TIDA-01614 board to have accurate temperature. Sensor is interfaced through I2C. This design patch operates on a 3.3-V and uses 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 remains static on the patient.

U1 is the TMP117 IC and J1 is the connector that interfaces to the TIDA-01614 main board.

Figure 20. Temperature Sensor Circuit



3.3.13 TI Devices

AFE4403

The AFE4403 is a fully-integrated analog front-end (AFE) supports pulse oximeter applications. The device consists of a low-noise receiver channel with an integrated analog-to-digital converter (ADC), an LED transmit section, and diagnostics for sensor, and LED fault detection. The device is a configurable timing controller. This flexibility enables the user to have complete control of the device timing characteristics. To ease clocking requirements and provide a low-jitter clock to the AFE4403, an oscillator is integrated from an external crystal. The device communicates to an external microcontroller or host processor using an SPI interface. The device is a complete AFE solution packaged in a single, compact DSBGA-36 (3.07-mm × 3.07-mm × 0.5-mm) and is specified over the operating temperature range of –20°C to 70°C.

TLV755P

The TLV755P is an ultra-small, low quiescent current, low-dropout regulator (LDO) that sources 500 mA with good load and line transient performance. The TLV755P is optimized for a wide variety of applications by supporting an input voltage range from 1.45 V–5.5 V. To minimize cost and solution size, the device is offered in fixed output voltages ranging from 0.6 V to 5 V to support the lower core voltages of modern MCUs. Additionally, the TLV755P has a low-IQ with enable functionality to minimize standby power. This device features an internal soft-start to lower inrush current, providing a controlled voltage to the load and minimizing the input voltage drop during start up. When shutdown, the device actively pulls down the output to quickly discharge the outputs and ensure a known start-up state.

The TLV755P is stable with small ceramic output capacitors allowing for a small overall solution size. A precision band-gap and error amplifier provides a typical accuracy of 1%. All device versions have integrated thermal shutdown, current limit, and undervoltage lockout (UVLO). The TLV755P has an internal foldback current limit that helps reduce the thermal dissipation during short-circuit events.

TPS61099

The TPS61099x device is a synchronous boost converter with 1-µA ultra-low quiescent current. The device is designed for products powered by an alkaline NiMH rechargeable battery, Lithium-Mn battery, or rechargeable Li-ion battery, for which high efficiency under light load condition is critical to achieve long battery life operation. The TPS61099x boost converter uses a hysteretic control topology to obtain maximal efficiency at minimal quiescent current. It only consumes 1-µA quiescent current under a light load condition and can achieve up to 75% efficiency at 10-µA load with fixed output voltage version. It can also support up to 300-mA output current from 3.3 V–5 V conversion, and achieve up to 93% at 200-mA load.

The TPS61099x also offers Down Mode and Pass-Through operations for different applications. In Down Mode, the output voltage can still be regulated at target values even when input voltage is higher than output voltage. In Pass-Through Mode, the output voltage follows input voltage. The TPS61099x exits Down Mode and enters into Pass-Through Mode when VIN > VOUT + 0.5 V. The TPS61099x supports true shutdown function when it is disabled, which disconnects the load from the input supply to reduce the current consumption. The TPS61099x offers both adjustable output voltage version and fixed output voltage versions. It is available in 6-ball 1.23-mm × 0.88-mm WCSP package and 6-pin 2-mm × 2-mm WSON package.

TPS76901

The TPS76901 low-dropout (LDO) voltage regulator offers the benefits of low-dropout voltage, ultra-low power operation, and miniaturized packaging. This regulator features low-dropout voltages and ultra-low quiescent current compared to conventional LDO regulators. The TPS76901 device is ideal for micropower operations and where board space is at a premium.

A combination of new circuit design and process innovation has enabled the usual PNP pass transistor to be replaced by a PMOS pass element. Because the PMOS pass element behaves as a low-value resistor, the dropout voltage is extremely low, and is directly proportional to the load current. Since the PMOS pass element is a voltage-driven device, the quiescent current is ultra-low (28 µA maximum) and is stable over the entire range of output load current (0 mA to 100 mA). It is intended for use in portable systems such as laptops and cellular phones. The ultra-low dropout voltage feature and ultra-low power operation result in a significant increase in system battery operating life. The TPS76901 also features a logic-enabled sleep mode to shut down the regulator, reducing quiescent current to 1 µA, which is typical at TJ = 25°C. The TPS76901 is a variable version programmable over the range of 1.2 V–4.5 V.

TLV62569

The TLV62569 device is a synchronous step-down buck DC/DC converter, optimized for high efficiency and compact solution size. The device integrates switches capable of delivering an output current up to 2 A. At medium to heavy loads, the device operates in pulse width modulation (PWM) mode with 1.5-MHz switching frequency. At light loads, the device automatically enters Power Save Mode (PSM) to maintain high efficiency over the entire load current range. In shutdown, the current consumption is reduced to less than 2 µA. The TLV62569 provides an adjustable output voltage through an external resistor divider. An internal soft start circuit limits the inrush current during startup. Other features like overcurrent protection, thermal shutdown protection, and power good are built-in. The device is available in a SOT23 and SOT563 package.

BQ24232

The BQ2423x devices are highly-integrated Li-ion linear chargers and system power-path management devices targeted to space-limited portable applications. The devices operate from either a USB port or AC adapter, and support charge currents between 25 mA and 500 mA. The high-input-voltage range with input overvoltage protection supports low-cost, unregulated adapters. The USB input current limit accuracy and start-up sequence let the BQ2423x meet the USB-IF inrush current specification. Additionally, the input dynamic power management (VIN-DPM) prevents the charger from crashing poorly-designed or incorrectly-configured USB sources.

The BQ2423x features dynamic power-path management (DPPM) that powers the system while simultaneously and independently charging the battery. The DPPM circuit reduces the charge current when the input current limit causes the system output to fall to the DPPM threshold, thus supplying the system load at all times while monitoring the charge current separately. This feature reduces the number of charge and discharge cycles on the battery, allows proper charge termination, and enables the system to run with a defective or absent battery pack. Additionally, this enables the system to instantly turn on, even with a totally discharged battery. The power-path management architecture also permits the battery to supplement the system current requirements when the adapter cannot deliver the peak system currents, enabling the use of a smaller adapter.

The battery is charged in three phases: conditioning, constant current, and constant voltage. In all charge phases, an internal control loop monitors the IC junction temperature and reduces the charge current if the internal temperature threshold is exceeded. The charger power stage and charge current sense functions are fully-integrated. The charger function has high-accuracy current and voltage regulation loops, charge status display, and charge termination. The input current limit and charge current are programmable using external resistors.

ADS1292R

The ADS1292R is a multichannel, simultaneous sampling, 24-bit, delta-sigma (ΔΣ) analog-to-digital converters (ADCs) with a built-in programmable gain amplifier (PGA), internal reference, and an onboard oscillator. The ADS1292R incorporates all features commonly required in portable, low-power medical ECG, sports, and fitness applications.

With high levels of integration and exceptional performance, the ADS1292R enables the creation of scalable medical instrumentation systems at significantly reduced size, power, and overall cost. The ADS1292R has a flexible input multiplexer per channel that can be independently connected to the internally-generated signals for test, temperature, and lead-off detection. Additionally, any configuration of input channels can be selected for derivation of the right leg drive (RLD) output signal. ADS1292R operates at data rates up to 8 kSPS. Lead-off detection can be internally implemented to the device, using the internal excitation current sink/source from the device. The ADS1292R also includes a fully-integrated respiration impedance measurement function. The devices are packaged in a 5-mm × 5-mm, 32-pin thin quad flat pack (TQFP). Operating temperature is specified from –40°C to +85°C.

TVS0500

The TVS0500 robustly shunts up to 43 A of IEC 61000-4-5 fault current to protect systems from high-power transients or lightning strikes. The device offers a solution to the common industrial signal line EMC requirement to survive up to 2 kV IEC 61000-4-5 open circuit voltage coupled through a 42 Ω impedance. The TVS0500 uses a unique feedback mechanism to ensure precise flat-clamping during a fault, assuring system exposure below 10 V. The tight voltage regulation lets designers confidently select system components with a lower voltage tolerance, lowering system costs and complexity without sacrificing robustness. In addition, the TVS0500 is available in a small 2-mm × 2-mm SON footprint, which is ideal for space-constrained applications. It offers a 70 percent reduction in size compared to industry standard SMA and SMB packages. The extremely-low device leakage and capacitance ensure a minimal effect on the protected line. To ensure robust protection over the lifetime of the product, TI tests the TVS0500 against 5000 repetitive surge strikes at high-temperatures with no shift in device performance.

MSP432P4011

The SimpleLink™ MSP432P401x MCUs are optimized host MCUs with an integrated 16-bit precision ADC. These MCUs deliver ultra-low power performance including 80 µA/MHz in active power and 660 nA in standby power with FPU and DSP extensions. As an optimized host MCU, the MSP432P401x lets developers add high-precision analog and memory extension to applications based on SimpleLink connectivity solutions.

The MSP432P401x devices are part of the SimpleLink MCU platform, consisting of Wi-Fi®, Bluetooth® low-energy, Sub-1 GHz, and host MCUs. These share a common, easy-to-use development environment with a single core software development kit (SDK) and rich tool set. A one-time integration of the SimpleLink platform lets you add any combination of devices from the portfolio into your design. The ultimate goal of the SimpleLink platform is to achieve 100% code reuse when your design requirements change. For more information, see the SimpleLink website.

MSP432P401x devices are supported by a comprehensive ecosystem of tools, software, documentation, training, and support to get your development started quickly. The MSP-EXP432P401R LaunchPad development kit or MSP-TS432PZ100 target socket board (with additional MCU sample) along with the free SimpleLink MSP432 SDK is all you need to get started.

4 Hardware, Software, Testing Requirements, and Test Results

4.1 Required Hardware and Software

4.1.1 Hardware

Hardware connection

Figure 21 and Figure 22 show top and bottom views of the TIDA-01614 PCB.

Figure 21. TIDA-01614 PCB Connector Configuration – Top View

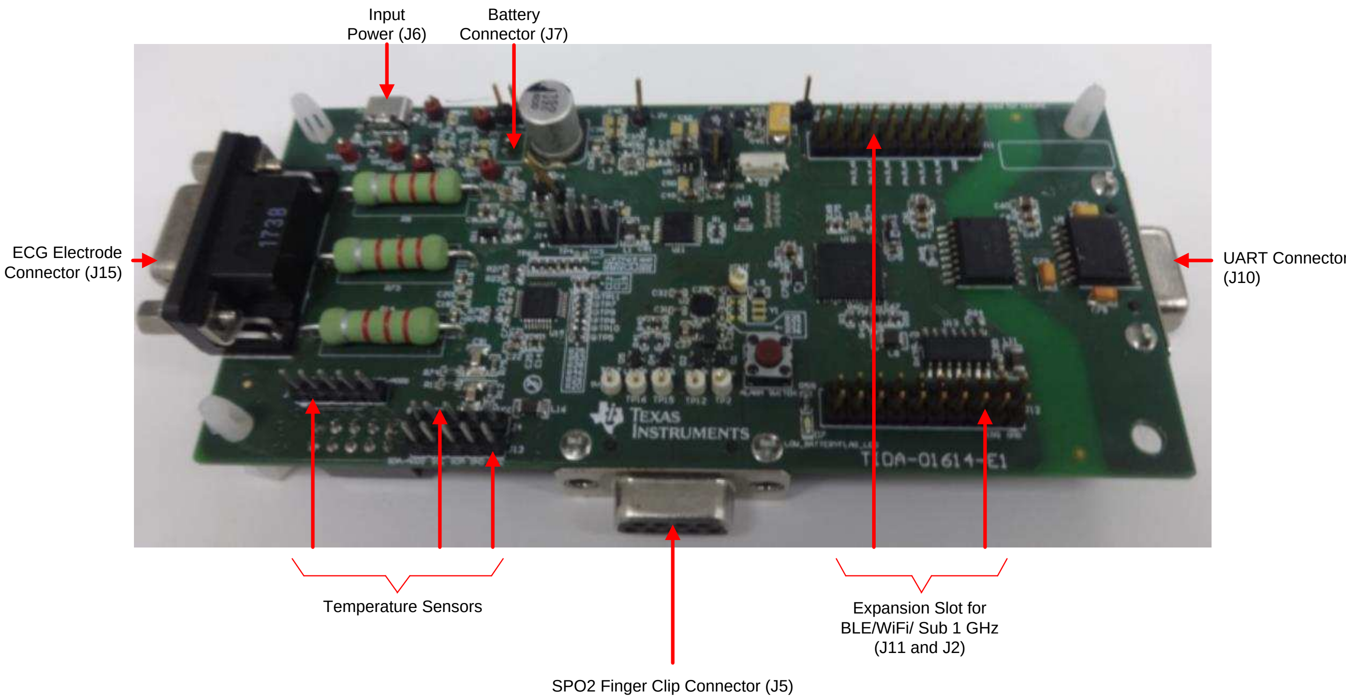
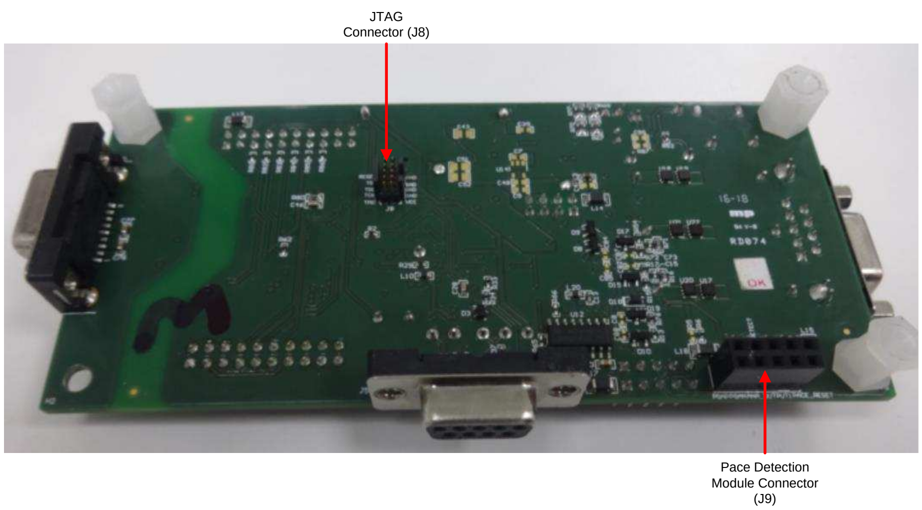


Figure 22. TIDA-01614 PCB Connector Configuration – Bottom View



The following list provides information about each part:

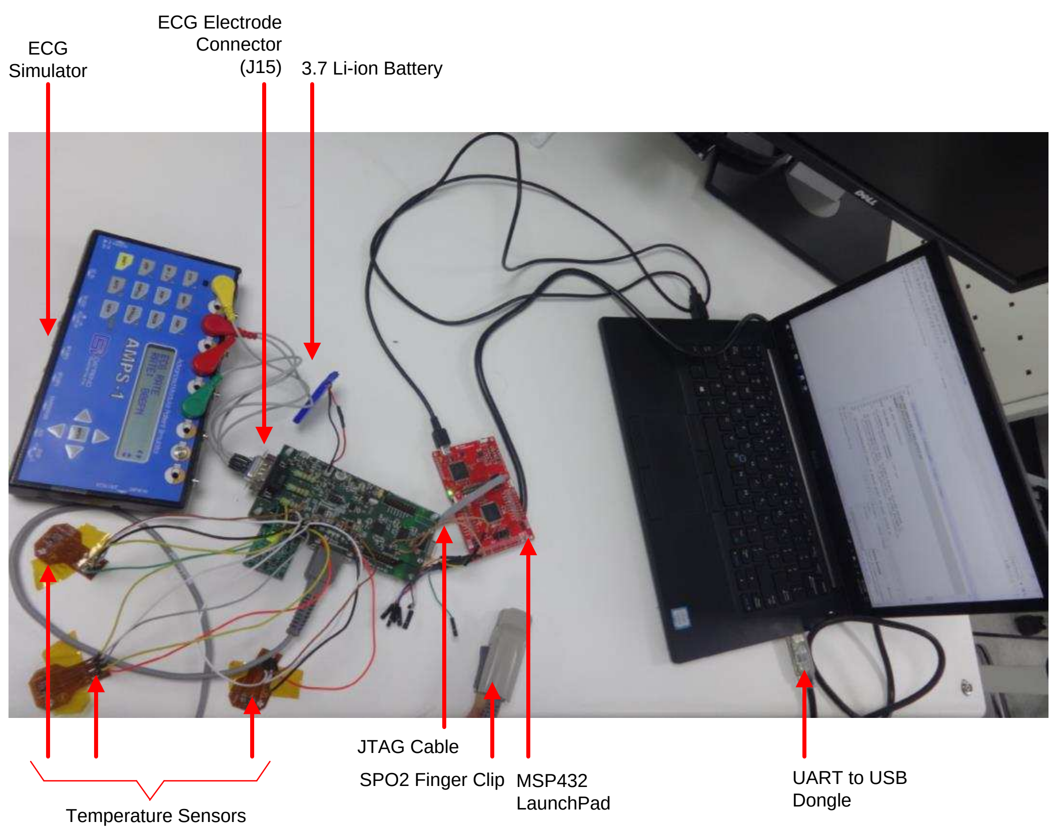
- **Input Power Connector (J6):** A USB-connector for 5-V input power 5 V. 5 V is derived from the USB Vbus.
- **Battery Connector (J7):** This pin connects the rechargeable 3.7-V Lithium-ion battery.

- **UART Connector (J10):** This connector is given as a provision to connect to the PC through serial port.
- **ECG Electrode Connector (J15):** This pin connects the ECG electrodes in 2 electrode and 3 electrode operations.
- **Temperature Sensor Connector (J3,J4 and J13):** These connectors connect the three temperature sensors.
- **SPO2 Finger Clip Connector (J5):** This connector connects the SPO2 finger clip.
- **Expansion Slot for BLE/WiFi/Sub 1 GHz (J11 and J12):** These connectors are the expansion slot for BLE/WiFi/Sub 1 GHz.
- **JTAG Connector (J8):** The JTAG connector is for programming.
- **Pace Detection Module connector (J9):** This connector connects the pace detection Module (TIDA-010005).
- **Isolated UART connector (J16) :** This connector is used to give the provision to have 3.3 V isolated UART signals. Connect the USB to UART Dongle (C232HD-DDHSP-0) from this connector to the PC.

4.1.2 Test Setup

Figure 23 shows the test setup. An ECG simulator (Datrend AMPS-1 Advanced Modular Patient Simulator) generates ECG, Respiration, and pace signal for testing. The TIDA-01614 board is programmed using the MSP432 launch pad, connecting to the PC. Three temperature sensor Flex PCBs are connected to this board. Flexi PCB can be easily strapped on to the human board for temperature measurement. Three such temperature sensors are used for accurate temperature measurement. Three ECG electrodes connected to the right arm, left arm, and right leg attach to this board using J15 connector. The system runs with a rechargeable 3.7-V 500 mAh Li-ion battery connected to J7 connector. C232HD – DDHSP-0 UART to USB serial cable is used for UART communication to the PC and GUI.

Figure 23. TIDA-01614 Test Setup



4.1.3 Software

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

- Code Composer Studio™, version 8 or higher. This software must be installed with MSP432P401 support.
- SimpleLink-MSP432P401-SDK Software. You can download it at http://www.ti.com/tool/simplelink-msp432-sdk.
- GUI Composer Run Time Engine. You can download it at http://software-dl.ti.com/ccs/non-esd/gui_composer/runtime/gcruntime-7.0.0-windows-installer.exe .

The following instructions assume that Code Composer Studio is installed on the PC. Download the GUI Composer application setup (zip file) and TIDA-01614 firmware (zip file) from the TIDA-01614 product page. Follow these instructions to download the software loading for the TIDA-01614 board:

1. Plug in the MSP EXP432P401R board on the USB port of the PC. Section 4.1.2 shows the setup. Table 2 lists the connections between the TIDA-01614 board and the MSP EXP432P401R) board.
2. Open Code Composer Studio as administrator.
   a. Right click on the CCS icon and run as administrator.
3. Click on the Project option in the main toolbar.
4. Click Import CCS projects.
5. Select the installed firmware (Default: C:\Program Files (x86)\Texas Instruments\TIDA01614\TIDA-01614_firmware).
6. Import all projects.
7. Click the OK button.
8. Click View.
9. Click Project Explorer.
10. Select TIDA-01614 firmware.
11. Click on the Run and Debug buttons, which program the board with the selected project file.

Go to https://dev.ti.com/gallery/info/5331888/med_tida01614/ver/1.0.1/ for the GUI composer. You must use Google Chrome to open the link. Use the following steps for the GUI composer.

Figure 24. Step 1

1. Click anywhere inside the card. A pop-up appears to download and install the TI cloud agent. Install it and click to finish.

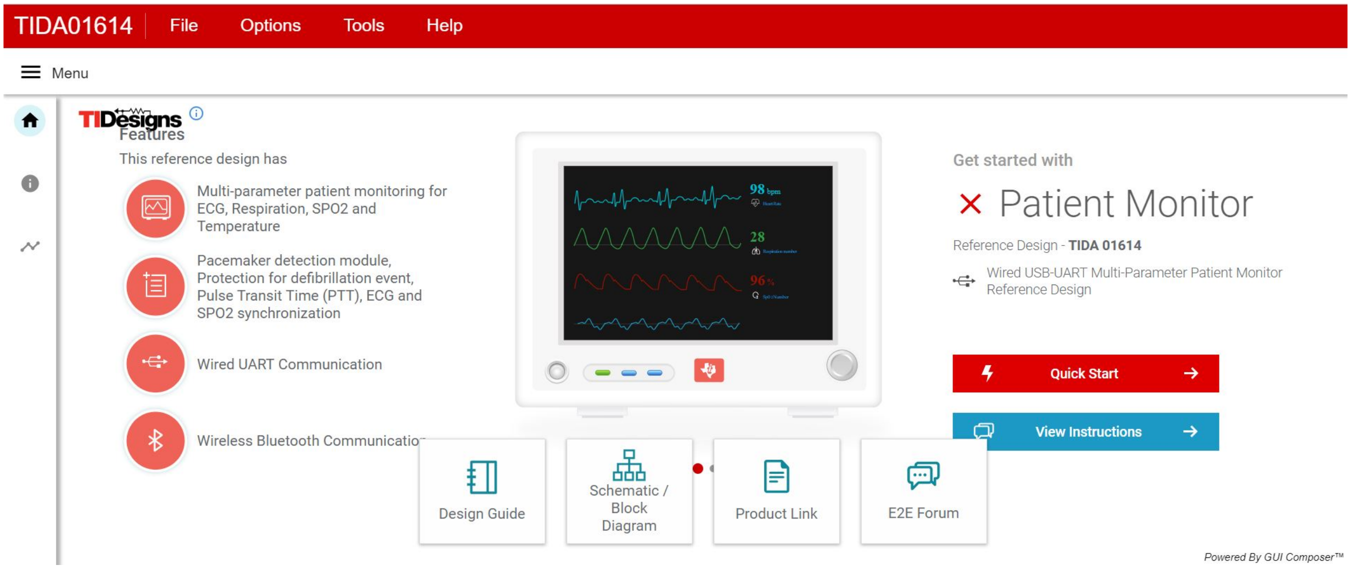


Figure 25. Step 2

2. Click on the Quick Start button.

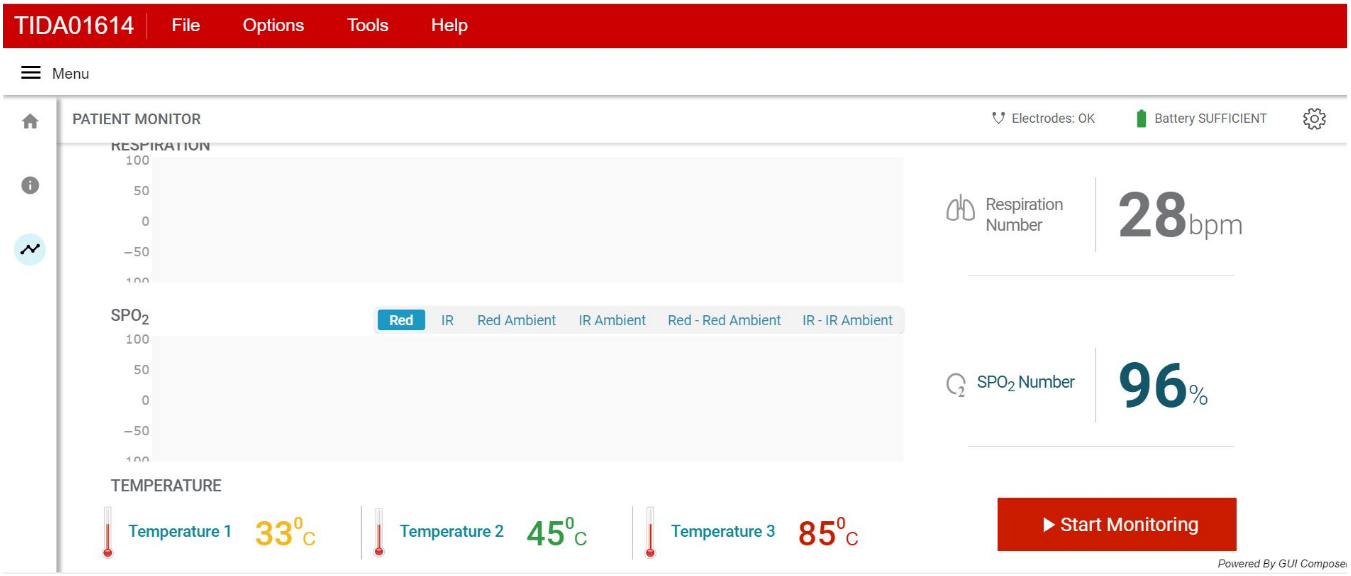


Figure 26. Step 3

3. Go to the Options tab.
4. Select 460800 as the baud rate and select the COM port for the USB to UART Dongle.
5. Click on the Start Monitoring button. Ensure that it shows that the hardware is connected on the bottom panel.

4.2 Test Results

4.2.1 Test Results

Figure 27. GUI Displaying ECG, SPO2 Waveforms With SPO2 Number and Heart Rate With ECG Sensitivity of 100-µVs

Figure 27 illustrates the GUI displaying ECG, SPO2 waveforms with SPO2 number, and heart rate with ECG sensitivity of 100-µVs.

Figure 28. GUI Displaying ECG, Respiration and SPO2 Waveforms With SPO2 Number and Heart Rate

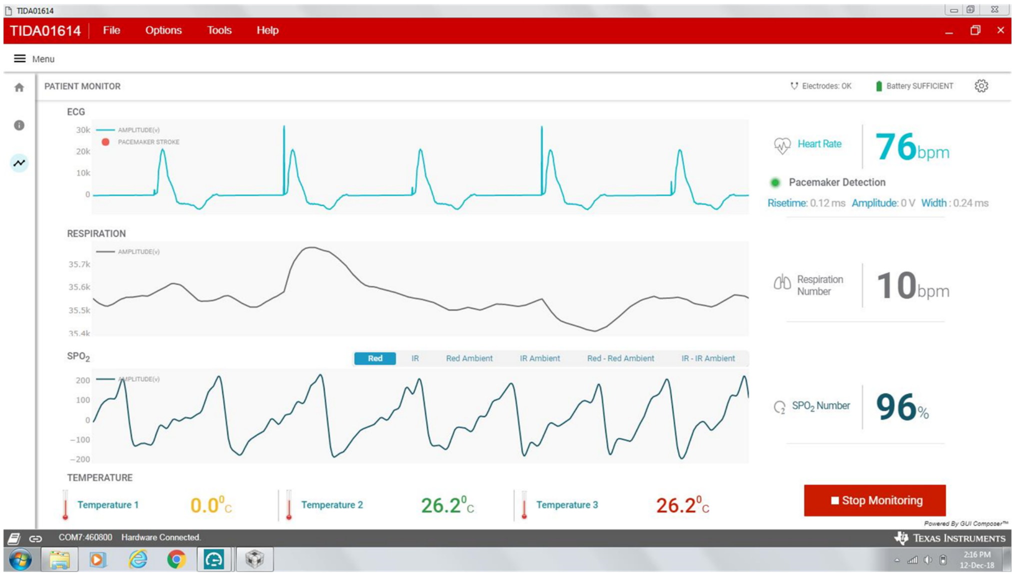


Figure 29. GUI Showing the Pacemaker Detection

Figure 29 illustrates the GUI showing the pacemaker detection. This result is captured with the respiration off.

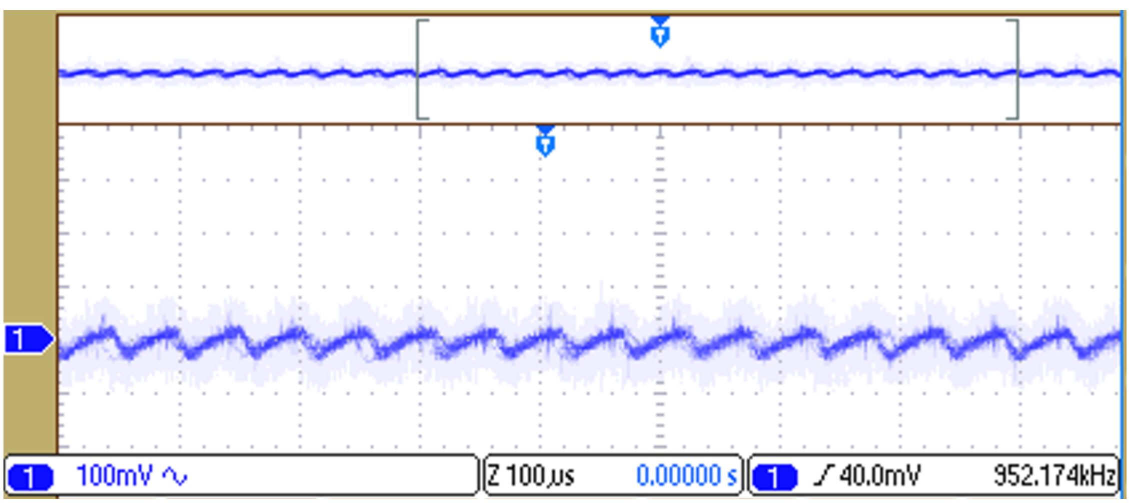


Figure 30. Output Ripple Voltage of 5.2 V Supply for Input Voltage of 3.7 V, and Input Current of 120 mA

Figure 30 shows the output ripple voltage of 5.2 V supply with input voltage of 3.7 V, and input current of 120 mA.

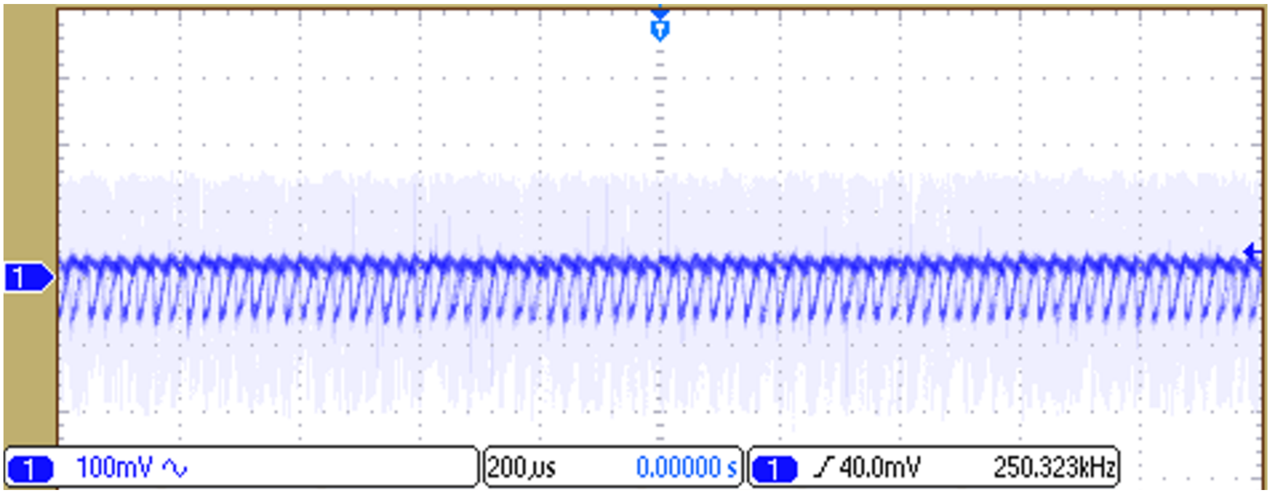


Figure 31. Output Ripple Voltage of 5 V Supply for Input Voltage of 3.7 V, and Input Current of 120 mA

Figure 31 shows the output ripple voltage of 5 V supply for input voltage of 3.7 V, and input current of 120 mA.

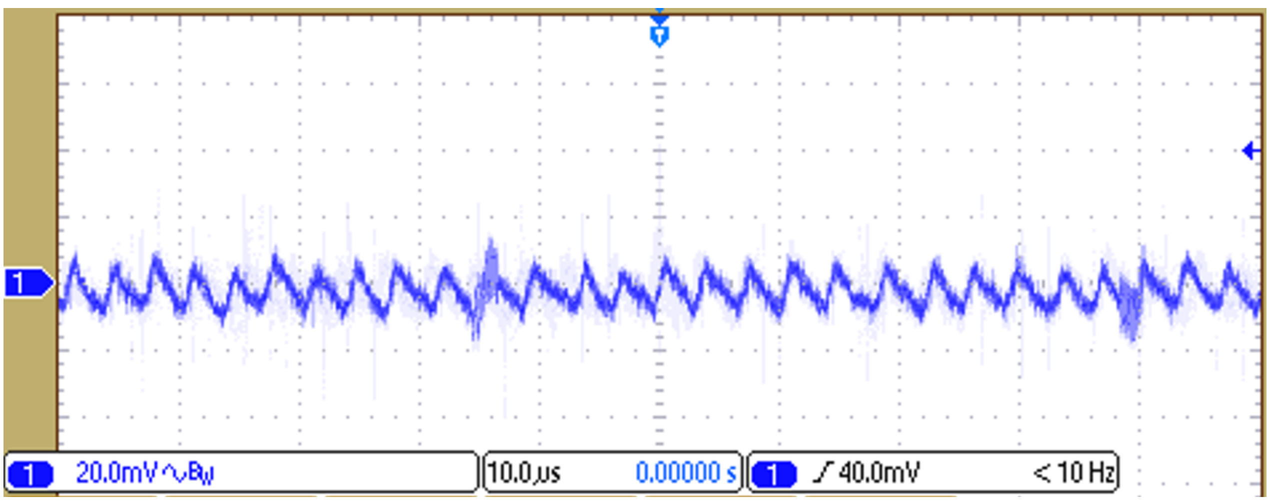


Figure 32. Output Ripple Voltage of 3.3 V Supply for Input Voltage of 3.7 V, and Input Current of 120 mA

Figure 32 shows the output ripple voltage of 3.3 V supply for input voltage of 3.7 V, and input current of 120 mA.

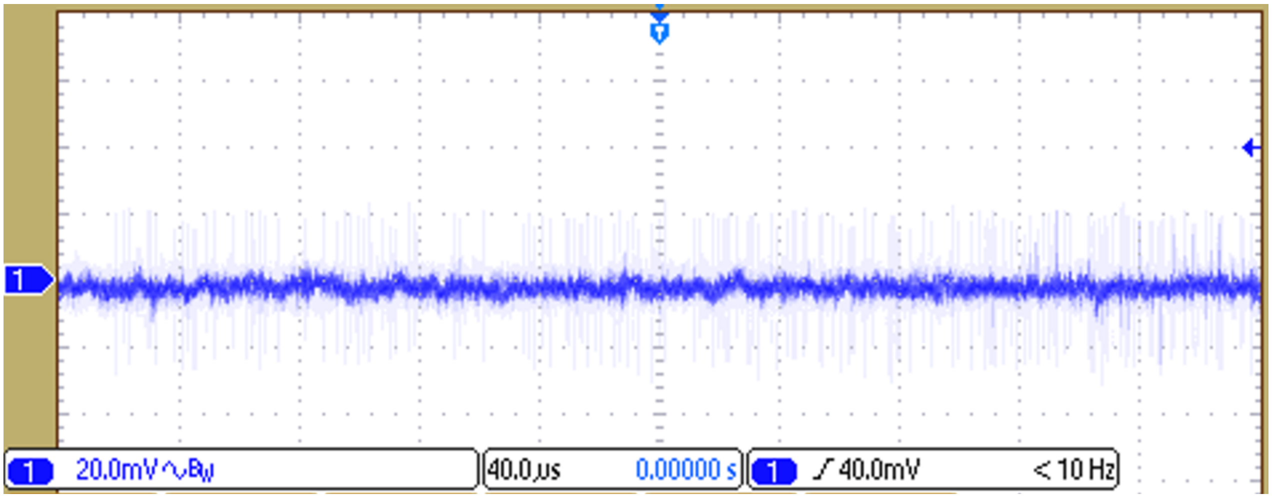


Figure 33. Output Ripple Voltage of 3.3 V Supply for Input Voltage of 3.7 V, and Input Current of 120 mA

Figure 33 shows the output ripple voltage of 3 V supply for input voltage of 3.7 V, and input current of 120 mA.

5 Design Files

5.1 Schematics

See the design files at TIDA-01614 to download the schematics.

5.2 Bill of Materials

See the design files at TIDA-01614 to download the bill of materials (BOM).

5.3 PCB Layout Recommendations

5.3.1 Layout Prints

See the design files at TIDA-01614 to download the layer plots.

5.4 Altium Project

See the design files at TIDA-01614 to download the Altium Designer® project files.

5.5 Gerber Files

See the design files at TIDA-01614 to download the Gerber files.

5.6 Assembly Drawings

See the design files at TIDA-01614 to download the assembly drawings.

6 Software Files

See the design files at TIDA-01614 to download the software files.

7 Related Documentation

1. Texas Instruments, *Minaturized pulse oximeter reference design getting started guide*
2. Texas Instruments, *How to design peripheral oxygen saturation (SpO_2) and optical heart rate monitoring (OHRM) systems using the AFE4403 application report*
3. Texas Instruments, *Understanding lead-off detection in ECG application report*

7.1 Trademarks

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8 About the Author

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Revision History

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

Changes from Original (March 2019) to A Revision	Page
• Changed *TIDA-01614 Block Diagram* image in *System Overview* and on first page	5