TI Designs: TIDA-01469

Motor Monitoring Using Wireless Vibration Sensor Reference Design Enabling Preventive Maintenance

Description

This reference design is a low-power wireless subsystem that monitors motors using vibration sensing to determine if preventative maintenance is necessary. An FFT of the vibration data can be sent out to another device using either *Bluetooth*® low energy or Sub-1 GHz wireless protocols. The low-power usage and wireless capabilities of this subsystem enables it to run on a single coin cell battery, which allows for the device to be small, inexpensive, and placed in difficult-to-reach locations. These features makes this design an ideal alternative to both expensive maintenance that could have been preventatively avoided as well as larger, more expensive monitors that require a wired connection.

Resources

TIDA-01469	Design Folder
CC1350	Product Folder
ADS8866	Product Folder
OPA2325	Product Folder
TPS61291	Product Folder
REF5030	Product Folder
TPS22860	Product Folder
LMT01	Product Folder
LAUNCHXL-CC1350	Tool Folder

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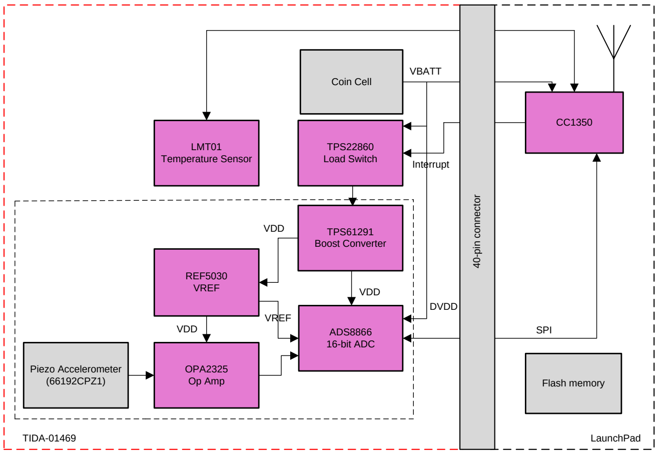
Features

- Ultra-Low-Power Design Resulting in 10-Year Battery Life From Single CR2032 Coin Cell
- Offers Mechanical Vibration (20 kSPS) and Temperature Sensing
- Local Computation of 2K FFT for Vibration Spectral Analysis
- Programmable Wake-Up Intervals for Motor Diagnostics
- Designed For SimpleLink™ Sub-1 GHz and Bluetooth Low Energy Wireless Connectivity LaunchPad™ (LAUNCHXL-CC1350)

Applications

- Remote Motor Health Monitoring
- Wireless Machine Monitoring
- Structural Monitoring



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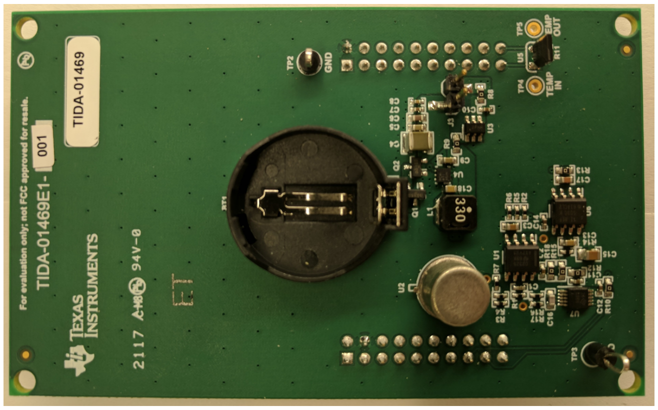

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1 System Description

Many industrial settings include motors that require maintenance as they age and stop working correctly. This maintenance is expensive, and significant downtime can occur if the need for maintenance is not predicted and accounted for. Wireless monitors that can run on a single coin cell battery can be placed almost anywhere and do not need to be accessed often, which is ideal for industrial settings.

The Motor Monitoring Using Wireless Vibration Sensor Reference Design provides a wireless motor monitoring subsystem that can run on a single CR2032 coin cell battery with 10+ year battery life. This allows for a small motor monitor that can be placed in difficult-to-reach locations and does not need to be reached often to change the battery or access the data with a wired connection.

This reference design uses Texas Instruments' CC1350 SimpleLink Ultra-Low Power Dual Band Wireless Microcontroller to read the sensor data, process this data by computing a 2K FFT, and send the data out over an ultra-low-power 2.4-GHz Bluetooth low energy or Sub-1 GHz network. The firmware provided in this design guide uses Texas Instruments' Bluetooth low energy software stack to send the FFT data out in notifications in a connection with another device.

At a high level, this reference design consists of a CR2032 coin cell battery, an ultra-low-power wireless MCU, a piezoelectric accelerometer to acquire the vibration data, an analog-to-digital converter (ADC) to sample this data, and a load switch and boost convertor to gate power to the system. The real-time clock on the CC1350 MCU is used to only wake the system at configurable time intervals. When the system is powered up, the accelerometer acquires the vibration data, the ADC converts the data and sends it to the MCU over SPI, the MCU computes the FFT of the data, and the data is sent to another device over Bluetooth low energy. The device that receives the data can then indicate that the motor monitor can power back down until it is time to take vibration measurements again. A temperature sensor is also provided to monitor the ambient temperature and further help to predict the need for motor maintenance.

This design guide addresses component selection, design theory, and the testing results of this reference design system. The scope of this design allows designers to develop motor monitoring applications that use TI's components for the analog front end (AFE) and TI's SimpleLink ultra-low-power wireless MCU platform.

The following subsections describe the key blocks within the reference design system and what characteristics are most critical to best implement the corresponding functions.

1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Input power source	CR2032 Lithium-ion coin cell battery (3.0-V nominal voltage)	Section 2.2.6
Sensor type	Accelerometer	Section 2.2.2
Average standby-state current	879.5 nA	Section 3.2.2.1
Estimated battery life	> 10 years	Section 3.2.2.2
Fourier transform	2048 points at 20 kSPS	Section 3.2.2.3
Frequency monitoring range	50 Hz to 10 kHz	Section 3.2.2.3
Operating temperature	–30°C to 85°C	Section 2.3
Wireless protocol	Bluetooth low energy	Section 2.4.3
Radio transmission range	72 meters	Section 3.2.2.5
Default reporting interval	8 hours (Can be dynamically selected)	Section 2.4.4
Form factor (sensor board)	58.50-mm × 95.30-mm rectangular PCB	Section 3.1.1

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2 System Overview

2.1 Block Diagram

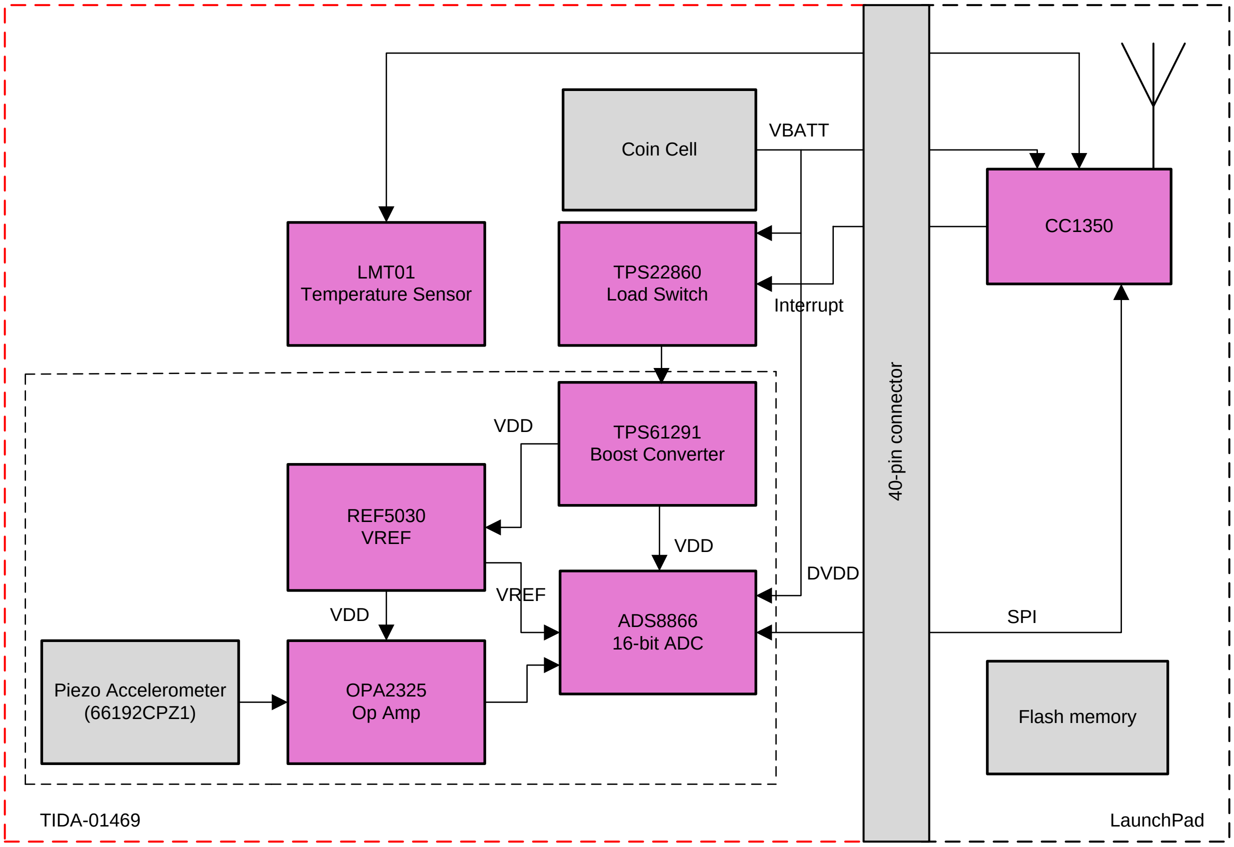

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Figure 1. Block Diagram

2.2 Design Considerations

2.2.1 Ultra-Low-Power Wireless MCU

In this reference design, the acquired vibration data and the FFT of the data need to be sent to another device so that it can be used to determine if maintenance is or will soon be necessary. To allow for a small device with a long enough battery life to justify putting the monitor in difficult-to-reach locations, however, the radio and processor must also be low power. The CC1350 has two antennas to allow data to be transmitted over either Bluetooth low energy or Sub-1 GHz networks, depending on what device will receive the data and how it will be stored and accessed. TI's SimpleLink ultra-low-power wireless MCU platform, with a combined radio and MCU, enables an extremely long battery life for wireless motor monitors.

2.2.2 Piezoelectric Accelerometer

Piezoelectric accelerometers can accurately measure vibrations, which allows for the health of the motor to be quantified. This reference design uses the 66192CPZ1 from IMI Sensors®. This device has a good sensitivity for the design, and its 10-kHz frequency range allows for a stable input signal to the ADC after filtering. It also has a high linearity, which allows for more accurate data.

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2.2.3 Analog-to-Digital Conversion

This reference design uses an ADC with external voltage reference to digitize the output of the op-amp stage. The ADS8866 is a 16-bit SAR ADC that provides the necessary resolution and sampling for the wireless motor monitor design. The device communicates with the MCU over SPI, and the high resolution allows for an accurate FFT to be calculated and observed. The digital power supply of the ADC is connected directly to the output of the battery to match the digital input/output pin voltage levels of the wireless MCU.

An external voltage reference source is used for the ADC to provide an output voltage that is stable across ambient temperature, loading, input supply, and time. The REF5030 device provides a low-noise, low-drift, very high-precision voltage reference. The standard grade device has an initial output voltage accuracy of ±0.1% (max), a temperature drift of 8 ppm/°C (max), a long-term stability of 45 ppm/1000 hr after 1000 hours (typ), and an output voltage noise of 3 $\mu V_{PP}/V$ (typ).

At a 100-kHz sampling rate, the ADC consumes 230 µA when operated at 3 V while the voltage reference has a quiescent current of 800 µA. To meet the battery life target for this reference design, it is necessary to completely power off the ADC and voltage reference when the system is in standby mode. The ADC and voltage reference are powered on when a vibration measurement is needed.

2.2.4 Low-Leakage Boost Converter

Some sensor end-nodes require a regulated voltage rail to operate at their highest levels of sensing performance. To provide a well-regulated voltage rail over the entire lifetime of the battery, a boost converter is necessary. However, to reduce the battery life loss due to converter inefficiency, an extremely high-efficiency boost converter is required.

In this reference design, the TPS61291 device regulates the battery voltage to 3.3 V. With a battery voltage of 3.0 V, the TPS61291 maintains an efficiency level greater than 95% at the load currents typical of a sensor end-node: 1 to 100 mA. Even at the depleted coin cell voltage of 2.0 V, the TPS61291 device maintains an efficiency level greater than 90% over the typical load current range of 1 to 100 mA.

The boost converter provides the operating voltage for the sensor subsystem of the design, which includes the operational amplifiers, ADC, and voltage reference.

2.2.5 Low-Leakage Load Switch

This reference design uses a low-leakage load switch to shut off power to the sensor subsystem of the design leaving only the CC1350 wireless MCU and temperature sensor with power. The sensor subsystem includes the boost converter, operational amplifiers, ADC, and voltage reference. The most important characteristic of this switch is the off-state leakage, because that leakage affects the overall battery life of the system significantly.

In this reference design, the TPS22860 device is the switch used to disconnect the sensor subsystem from the battery. The TPS22860 has a typical leakage current of 2 nA at the VIN pin and 10 nA at the VBIAS pin, which enables extremely long battery life in this system.

2.2.6 Coin Cell Battery

The power source for this reference design is a CR2032 lithium-ion coin cell. The CR2032 coin cell battery is the power source because of the ubiquity of that battery type.

The voltage characteristics of a lithium-ion CR2032 coin cell battery are also ideal. The output voltage remains relatively flat throughout the discharge life until the cell is nearly depleted. When the cell is depleted, the output voltage drops off relatively quickly.

Immediately following the battery are two low R_{DS_ON} P-channel MOSFETs and a bulk capacitor. The P-channel MOSFETs prevent damage to the hardware if the coin cell battery is inserted backwards while minimizing the forward voltage drop in normal operation. The bulk capacitor is sized to prevent too much voltage drop, particularly during the transitions into the MCU on-state for radio transmissions.

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2.3 Highlighted Products

This motor monitoring reference design features the following devices:

- OPA2325 (Section 2.3.1): Dual, precision, low-voltage CMOS operational amplifier
- ADS8866 (Section 2.3.2): 16-bit, 100-kSPS, single-ended input, SAR analog-to-digital converter
- REF5030 (Section 2.3.3): Low-noise, low-drift, very high precision voltage reference
- TPS61291 (Section 2.3.4): Low-I_Q boost converter
- TPS22860 (Section 2.3.5): Ultra-low leakage current, single-channel load switch
- LMT01 (Section 2.3.6): High-accuracy, 2-pin temperature sensor
- CC1350 (Section 2.3.7): Ultra-low-power wireless SimpleLink MCU capable of handling both Sub-1 GHz and 2.4-GHz RF frequencies

For more information on each of these devices, see their respective product folders at TI.com.

2.3.1 OPA2325

The OPA2325 device is a dual, precision, low-voltage complementary metal oxide semiconductor (CMOS) operational amplifier optimized for very low noise and wide bandwidth when operating on a low quiescent current of only 650 µA.

The OPA2325 features a linear input stage with zero-crossover distortion that delivers excellent common-mode rejection ratio (CMRR) of typically 114 dB over the entire input range. The input common-mode range extends 100 mV beyond the negative and positive supply rails. The output voltage typically swings within 10 mV of the rails.

The zero-crossover distortion combined with wide bandwidth (10 MHz), high slew rate (5 V/µs), and low noise (9 nV/√Hz) make the OPA2325 a very good successive-approximation register (SAR) ADC input driver amplifier. The low offset, and 0.2-pA input bias current make this device ideal for a wide range of precision applications with high-impedance sensors. The unique feature of interfacing to high-impedance sensors on the input and being able to drive ADC inputs with very little distortion make the OPA2325 suitable for various data acquisition and process control applications.

In addition, the OPA2325 has a wide supply voltage range from 2.2 to 5.5 V with excellent power-supply rejection ratio (PSRR) over the entire supply range, making the device suitable for precision, low-power applications that run directly from batteries without regulation.

Key features of this device include:

- Precision with zero-crossover distortion:
  - Low offset voltage: 150 µV (max)
  - High CMRR: 114 dB
  - Rail-to-rail I/O
- Wide bandwidth: 10 MHz
- Quiescent current: 650 µA/ch
- Single-supply voltage range: 2.2 to 5.5 V
- Low input bias current: 0.2 pA
- Low noise: 9 nV/√Hz at 10 kHz
- Slew rate: 5 V/µs
- Unity-gain stable

2.3.2 ADS8866

The ADS8866 is a 16-bit, 100-kSPS, single-ended input ADC. The device operates with a 2.5- to 5-V external reference, offering a wide selection of signal ranges without additional input signal scaling. The reference voltage setting is independent of, and can exceed, the analog supply voltage (AVDD).

The device offers an SPI-compatible serial interface that also supports daisy-chain operation for cascading multiple devices.

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The device supports unipolar single-ended analog inputs in the range of –0.1 V to V_{REF} + 0.1 V.

Device operation is optimized for very low-power operation. Power consumption directly scales with speed. This feature makes the ADS8866 excellent for lower-speed applications.

Key features of this device include:

- Sample rate: 100 kHz
- No latency output
- Unipolar, single-ended input range: 0 to +VREF
- SPI-compatible serial interface with daisy-chain option
- Excellent AC and DC performance:
  - SNR: 93 dB, THD: –108 dB
  - INL: ±1.0 LSB (typ), ±2.0 LSB (max)
  - DNL: ±1.0 LSB (max), 16-bit NMC
- Wide operating range:
  - AVDD: 2.7 to 3.6 V
  - DVDD: 1.65 to 3.6 V (independent of AVDD)
  - Operating temperature: –40°C to 85°C
- Low-power dissipation:
  - 0.7 mW at 100 kSPS
  - 70 µW at 10 kSPS
- Power-down current (AVDD): 50 nA
- Full-scale step settling to 16 bits: 1200 ns
- Packages: MSOP-10 and SON-10

2.3.3 REF5030

The REF5030 is a low-noise, low-drift, very high-precision voltage references. These references are capable of both sinking and sourcing current and have excellent line and load regulation.

Excellent temperature drift (3 ppm/°C) and high accuracy (0.05%) are achieved using proprietary design techniques. Combined with very low noise, these features make the REF5030 device ideal for use in high-precision data acquisition systems.

Each reference voltage is available in both high grade (REF50xxIDGK and REF50xxID) and standard grade (REF50xxAIDGK and REF50xxAID). The reference voltages are offered in 8-pin VSSOP and SOIC packages and are specified from –40°C to 125°C.

Key features of this device include:

- Low temperature drift:
  - High-grade: 3 ppm/°C (Max)
  - Standard-grade: 8 ppm/°C (Max)
- High accuracy:
  - High-grade: 0.05% (Max)
  - Standard-grade: 0.1% (Max)
- Low noise: 3 µV_{PP}/V
- Excellent long-term stability:
  - 45 ppm/1000 hr (typ) after 1000 hours
- High-output current: ±10 mA
- Temperature range: –40°C to 125°C

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2.3.4 TPS61291

The TPS61291 is a boost converter with pin mode. In bypass operation, the device provides a direct path from the input to the system and allows a low-power MCU such as the MSP430™ to operate directly from a single 3-V Li-MnO2 battery or dual alkaline battery cells. In bypass mode, the integrated feedback divider network for boost mode operation is disconnected from the output and the quiescent current consumption drops down to only 15 nA (typical).

In boost mode, the device provides a minimum output current of 200 mA at 3.3-V V_{OUT} from 1.8-V V_{IN}. The boost mode is used for system components that require a regulated supply voltage and cannot directly operate from the input source. The boost converter is based on a current-mode controller using synchronous rectification to obtain maximum efficiency and consumes typically 5.7 µA from the output. During startup of the boost converter, the VSEL pin is read out and the integrated feedback network sets the output voltage to 2.5 V, 3 V, or 3.3 V.

Bypass mode or boost mode operation is controlled by the system through the EN/BYP pin.

The device integrates an enhanced bypass mode control to prevent charge, stored in the output capacitor during boost mode operation, from flowing back to the input and charging the battery.

The device is packaged in a small 6-pin SON package (DRV) measuring 2.0 mm × 2.0 mm x 0.75 mm.

Key features of this device include:

- Input voltage range: 0.9 to 5 V
- Startup voltage: 1.5 V at 20-mA load
- Pin selectable output voltages: 3.3 V, 3 V, 2.5 V
- 15-nA typical quiescent current in bypass mode
- 5.7-µA typical quiescent current in boost mode
- Bypass switch from V_{IN} to V_{OUT}
- $I_{OUT} > 200$ mA at 3.3-V V_{OUT}, $V_{IN} = 1.8$ V
- Internal feedback divider disconnect (bypass mode)
- Controlled bypass transition prevents reverse current into battery
- Power-save mode at light loads
- Overtemperature protection
- Redundant overvoltage protection
- Small 2-mm×2-mm SON 6-pin package

2.3.5 TPS22860

The TPS22860 is a small, ultra-low leakage current, single-channel load switch. The device requires a V_{BIAS} voltage and can operate over an input voltage range of 0 V to V_{BIAS}. The device can support a maximum continuous current of 200 mA. The switch is controlled by an on/off input (ON), which is capable of interfacing directly with low-voltage control signals. The TPS22860 is available in two small, space-saving 6-pin SOT-23 and SC70 packages. The device is characterized for operation over the free-air temperature range of –40°C to 85°C.

- Integrated single-channel load switch
- Bias voltage range (V single channel load switch. The device requires a BIAS): 1.65 to 5.5 V
- Input voltage range: 0 V to V_{BIAS}
- ON-resistance (R_{ON})
  - $R_{ON} = 0.73\ \Omega$ at $V_{IN} = 5$ V ($V_{BIAS} = 5$ V)
  - $R_{ON} = 0.68\ \Omega$ at $V_{IN} = 3.3$ V ($V_{BIAS} = 5$ V)
  - $R_{ON} = 0.63\ \Omega$ at $V_{IN} = 1.8$ V ($V_{BIAS} = 5$ V)
- 200-mA maximum continuous switch current
- Ultra-low leakage current
  - V_{IN} leakage current = 2 nA

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  - V_{BIAS} leakage current at 5.5 V = 10 nA
- 6-pin SOT-23 or SC70 package
- ESD performance tested per JESD 22
  - 2-kV HBM and 1-kV CDM

2.3.6 LMT01

The LMT01 device is a high-accuracy, 2-pin temperature sensor with an easy-to-use pulse count current loop interface, which makes it suitable for onboard and off-board applications in automotive, industrial, and consumer markets. The LMT01 digital pulse count output and high accuracy over a wide temperature range allow pairing with any MCU without concern for integrated ADC quality or availability, while minimizing software overhead. TI’s LMT01 device achieves a maximum ±0.5°C accuracy with very fine resolution (0.0625°C) over a temperature range of –20°C to 90°C without system calibration or hardware and software compensation.

The LMT01’s pulse count interface is designed to directly interface with a GPIO or comparator input, thereby simplifying hardware implementation. Similarly, the LMT01's integrated EMI suppression and simple 2-pin architecture makes it suitable for onboard and off-board temperature sensing in a noisy environment. The LMT01 device can be easily converted into a two-wire temperature probe with a wire length up to two meters. See LMT01-Q1 for the automotive qualified version.

Key features of this device include:

- High accuracy over –50°C to 150°C wide temperature range:
  - –20°C to 90°C: ±0.5°C (maximum)
  - 90°C to 150°C: ±0.625°C (maximum)
  - –50°C to –20°C: ±0.7°C (maximum)
- Precision digital temperature measurement simplified in a 2-pin package
- Pulse count current loop easily read by processor
  - Number of output pulses is proportional to temperature with 0.0625°C resolution
- Communication frequency: 88 kHz
- Conversion current: 34 µA
- Continuous conversion plus data-transmission period: 100 ms
- Floating 2- to 5.5-V (VP–VN) supply operation with integrated EMI immunity
- Multiple 2-pin package offerings: TO-92/LPG (3.1 mm × 4 mm × 1.5 mm)
  - ½ the size of traditional TO-92 and WSON with wettable flanks

2.3.7 CC1350

The CC1350 is a member of the CC26xx and CC13xx family of cost-effective, ultra-low-power, 2.4-GHz and Sub-1 GHz RF devices from Texas Instruments. Very low active RF and MCU current consumption, in addition to flexible low-power modes, provide excellent battery lifetime and allow long-range operation on small coin cell batteries and in energy-harvesting applications.

The CC1350 is the first device in the CC13xx and CC26xx family of cost-effective, ultra-low-power wireless MCUs capable of handling both Sub-1 GHz and 2.4-GHz RF frequencies. The CC1350 device combines a flexible, very low-power RF transceiver with a powerful 48-MHz ARM® Cortex® M3 MCU in a platform supporting multiple physical layers and RF standards. A dedicated radio controller (Cortex-M0) handles low-level RF protocol commands that are stored in ROM or RAM, thus ensuring ultra-low power and flexibility to handle both Sub-1 GHz protocols and 2.4-GHz protocols (for example, Bluetooth low energy). This enables the combination of a Sub-1 GHz communication solution that offers the best possible RF range together with a Bluetooth low energy smartphone connection that enables great user experience through a phone application. The Sub-1 GHz only device in this family is the CC1310.

The CC1350 device is a highly integrated, true single-chip solution incorporating a complete RF system and an on-chip DC-DC converter.

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Sensors can be handled in a very low-power manner by a dedicated autonomous ultra-low-power MCU that can be configured to handle analog and digital sensors; thus the main MCU (Cortex-M3) can maximize sleep time.

The CC1350 power and clock management and radio systems require specific configuration and handling by software to operate correctly, which has been implemented in the TI-RTOS. TI recommends using this software framework for all application development on the device. The complete TI-RTOS and device drivers are offered in source code free of charge.

Key features of this device include:

- Microcontroller:
  - Powerful ARM Cortex-M3 processor
  - EEMBC CoreMark® Score: 142
  - EEMBC ULPBench™ Score: 158
  - Clock speed up to 48 MHz
  - 128kB of in-system programmable flash
  - 8kB of SRAM for cache (or as general-purpose RAM)
  - 20kB of ultra-low-leakage SRAM
  - 2-pin cJTAG and JTAG debugging
  - Supports over-the-air (OTA) update
- Ultra-low-power sensor controller
  - Can run autonomously from the rest of the system
  - 16-bit architecture
  - 2kB of ultra-low-leakage SRAM for code and data
- Efficient code-size architecture, placing parts of TI-RTOS, drivers, Bluetooth low energy controller, and bootloader in ROM
- RoHS-compliant package
  - 7-mm×7-mm RGZ VQFN48 (30 GPIOs)
  - 5-mm×5-mm RHB VQFN32 (15 GPIOs)
  - 4-mm×4-mm RSM VQFN32 (10 GPIOs)
- Peripherals
  - All digital peripheral pins can be routed to any GPIO
  - Four general-purpose timer modules (eight 16-bit or four 32-bit timers, PWM each)
  - 12-bit ADC, 200 kSPS, 8-channel analog MUX
  - Continuous time comparator
  - Ultra-low-power clocked comparator
  - Programmable current source
  - UART
  - 2× SSI (SPI, MICROWIRE, TI)
  - I^2C, I2S
  - Real-time clock (RTC)
  - AES-128 security module
  - True random number generator (TRNG)
  - Support for eight capacitive sensing buttons
  - Integrated temperature sensor
- External system
  - On-chip internal DC-DC converter
  - Seamless integration with the SimpleLink CC1190 and CC2592 range extenders
- Low power

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  - Wide supply voltage range: 1.8 to 3.8 V
  - RX: 5.4 mA (Sub-1 GHz), 6.4 mA (Bluetooth low energy, 2.4 GHz)
  - TX at 10 dBm: 13.4 mA (Sub-1 GHz)
  - TX at 9 dBm: 22.3 mA (Bluetooth low energy, 2.4 GHz)
  - TX at 0 dBm: 10.5 mA (Bluetooth low energy, 2.4 GHz)
  - Active-mode MCU: 48 MHz running Coremark: 2.5 mA (51 µA/MHz)
  - Active-mode MCU: 48.5 CoreMark/mA
  - Active-mode sensor controller at 24 MHz: 0.4 mA + 8.2 µA/MHz
  - Sensor controller, one wakeup every second performing one 12-bit ADC sampling: 0.95 µA
  - Standby: 0.7 µA (RTC running and RAM and CPU retention)
  - Shutdown: 185 nA (wakeup on external events)
- RF section
  - 2.4-GHz RF transceiver compatible with Bluetooth low energy 4.2 specification
  - Excellent receiver sensitivity: –124 dBm using long-range mode, –110 dBm at 50 kbps (Sub-1 GHz), –87 dBm at Bluetooth low energy
  - Excellent selectivity (±100 kHz): 56 dB
  - Excellent blocking performance (±10 MHz): 90 dB
  - Programmable output power up to 15 dBm (Sub-1 GHz) and 9 dBm at 2.4 GHz (Bluetooth low energy)
  - Single-ended or differential RF interface
  - Suitable for systems targeting compliance with worldwide radio frequency regulations
    - ETSI EN 300 220, EN 303 204 (Europe)
    - EN 300 440 Class 2 (Europe)
    - EN 300 328 (Europe)
    - FCC CFR47 Part 15 (US)
    - ARIB STD-T66 (Japan)
    - ARIB STD-T108 (Japan)
  - Wireless M-Bus and selected IEEE® 802.15.4g PHY
- Tools and development environment
  - Full-feature and low-cost development kits
  - Multiple reference designs for different RF configurations
  - Packet sniffer PC software
  - Sensor Controller Studio
  - SmartRF™ Studio
  - SmartRF Flash Programmer 2
  - IAR Embedded Workbench® for ARM
  - Code Composer Studio™

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2.4 System Design Theory

2.4.1 Analog Front End

To monitor machine vibrations, this design uses a piezo vibration sensor. Because piezo sensors have high-impedance output nodes, the AFE circuitry was carefully designed to reduce the noise and increase the sensitivity of the system. For the AFE circuitry with piezo sensor, see Figure 2. The amplifier and the sensor affect the noise and sensitivity values of the AFE. Because of this effect, proper modeling of the sensor helps to analyze the noise and sensitivity of the AFE. Piezoelectric vibration sensors are typically used in much lower-frequency domains than resonant frequency. These sensors can be electrically modeled as a voltage source that converts force to voltage through two capacitors, C_1 and C_2. For these capacitors, see Figure 2. This model disregards the noise of the sensor because it is typically much less than the noise of the interface circuitry.

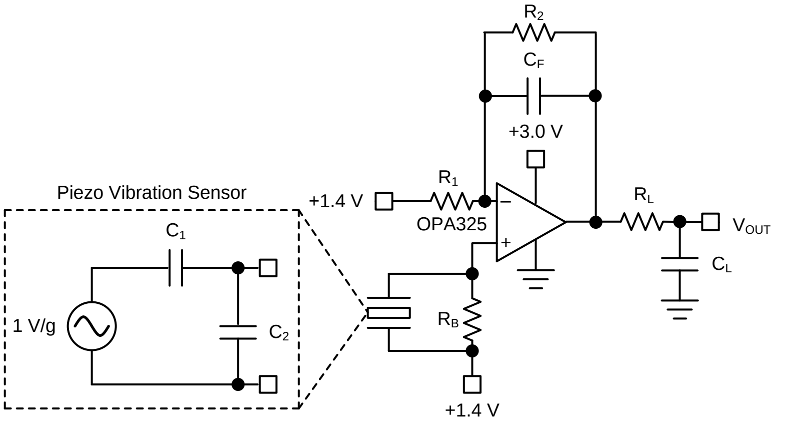

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Figure 2. AFE Schematic With Piezo Vibration Sensor

The sensitivity at the sensor output, S_S, is defined by Equation 1.

$$S_S = \frac{C_1}{C_1 + C_2 + C_{IN}} \tag{1}$$

where:

- C_{IN} is the input common-mode capacitor of the amplifier

Because a large C_{IN} reduces the S_S, it is desirable to make C_{IN} small in comparison to C_2. However, because the piezo sensors are high-impedance output sensors, CMOS or JFET input amplifiers are desirable but typically have large C_{IN} for low flicker noise. The OPA325 and the PCB Piezotronics sensor result in good performance when these constraints are taken into consideration because the C_{IN} of the OPA325 is 4 pF, which is very small compared to the 350 pF of the PCB Piezotronics sensor capacitance, and the OPA325 has low-input referred voltage noise, V_n, and low-input referred current noise, I_n.

The sensitivity of the amplifier output, S_{AMP}, is defined by Equation 2.

$$S_{AMP} = \frac{C_1}{C_1 + C_2 + C_{IN}} \times \left(1 + \frac{R_2}{R_1}\right) \tag{2}$$

The resistor, R_B, is necessary for the DC bias at the amplifier input, and it sets a high-pass filter with the sensor output capacitance.

The cut-off frequency of the high-pass filter $\approx \frac{1}{2\pi R_B C_2}$.

The capacitors, C_F and C_L, set low-pass filters with R_2 and R_L, respectively.

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The cutoff frequency of low-pass filter 1 is shown in Equation 3.

$$\frac{1}{2\pi R_L C_L} \tag{3}$$

The cutoff frequency of low-pass filter 2 is shown in Equation 4.

$$\frac{1}{2\pi R_2 C_F} \tag{4}$$

A TINA-TI™ simulation is run to determine the upper and lower cutoff frequencies. The upper cutoff frequency is shown to be 11.3 kHz, as shown in Figure 3.

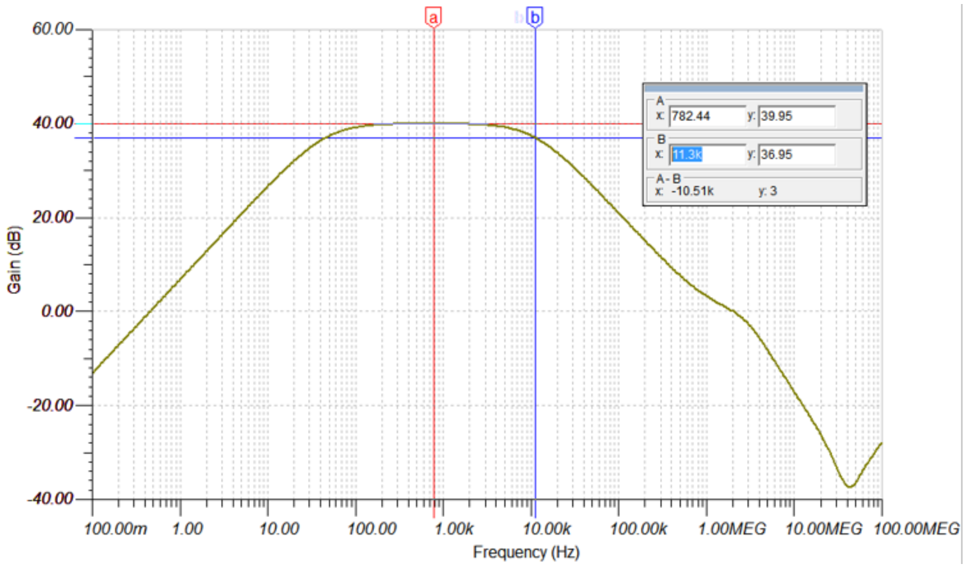

Figure 3. Upper Cutoff Frequency TINA-TI Simulation

The lower cutoff frequency is shown to be 45 Hz, as shown in Figure 4.

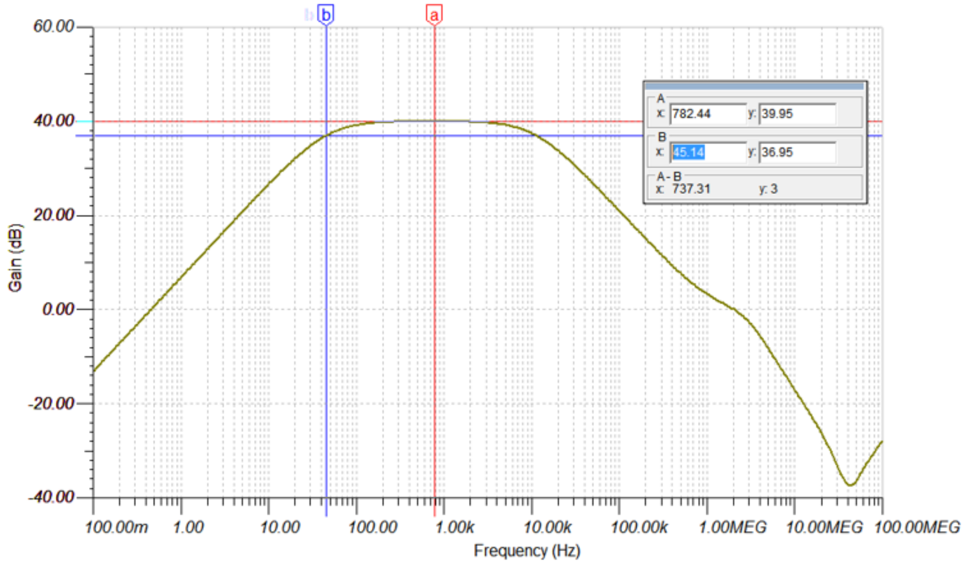

Figure 4. Lower Cutoff Frequency TINA-TI Simulation

These cutoff frequencies are verified by varying the input signal generated by the function generator given to the reference design and viewing the amplified signal that was provided as an input to the ADC.

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The noise at the amplifier input can be calculated as shown in Equation 5.

$$\sqrt{4kT \times R_1 / / R_2 + V_n^2 + I_n^2 \times (R_1 / / R_2)^2 + \left(I_n^2 + \frac{4kT}{R_B}\right) \times \left(\frac{1}{2\pi f \times (C_2 + C_{IN})}\right)^2} \tag{5}$$

Here the assumption is that $C_1 \ll C_{IN}$ and C_2, and $R_B \gg \frac{1}{2\pi f\,(C_2 + C_{IN})}$.

Finally, the input referred noise of the AFE including the sensor can be calculated as shown in Equation 6.

$$\frac{\text{Noise at the amplifier input}}{S_S} \tag{6}$$

The design parameters are shown in Table 2.

Table 2. Design Parameter Examples

DESIGN PARAMETER	VALUE
C_1	5 pF
C_2	350 pF
C_{IN}	4 pF
R_B	10 MΩ
R_1	100 Ω
R_2	10 kΩ
Gain	101
The sensitivity at the sensor output, S_S	14 mV/g
The sensitivity at the amplifier output, S_{AMP}	1.4 V/g
Noise at the amplifier input at 1 kHz	19.2 nV/√Hz
Input referred noise of the AFE at 1 kHz	1.4 µg/√Hz
Low cutoff frequency	45 Hz
High cutoff frequency	11.3 kHz

2.4.2 Power Supply Design

Because of the increasing battery impedance over the life of the battery supply, it is important to design the power supply network to prevent current spikes generated by the MCU from causing false triggers. While a software algorithm can help to filter such problems, this unwanted power supply feedback loop can become an issue. Ideally, the sensor supply would be regulated to break this loop; however, in this design, the extra quiescent current of a regulator reduces battery life, so other methods were explored.

Figure 5 shows a simplified schematic of the power supply network. The PMOS transistor is used in place of the traditional Schottky diode for reversed battery protection. Because the peak currents are in the 10-mA range when the radio transmits, using a low R_{DS_ON} PMOS provides a much lower voltage drop compared to a Schottky diode, which helps to maximize battery life by allowing the battery to decay to a lower voltage before the circuit is no longer able to function (for more on this technique, see the application report *Reverse Current/Battery Protection Circuits*[1] (SLVA139).

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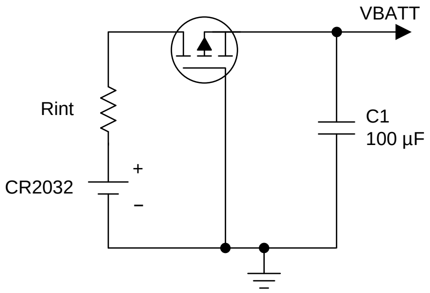

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Figure 5. Simplified Power Supply Network Schematic

Capacitor C1 supplies the circuit during periods of high and fast peak current demand, which helps to maximize the battery capacity and minimize voltage droop on the power supply rail, especially as the battery approaches its end of life and its internal impedance increases (represented by Rint in Figure 5). The calculation for C1 is provided in Equation 7. For more details on this calculation and the effects of high current peaks on battery life and capacity, see the white paper *Coin cells and peak current draw*[2] (SWRA349).

$$C2 = \frac{\Delta Q}{V_{MAX}} - V_{MIN} \quad (7)$$

where:

- $\Delta Q = Q_{dis} - \frac{V_{MIN}}{Rint} \times t_{tot}$
- $Q_{dis} = \sum i_n \times t_n$

V_{MAX} is the voltage across the capacitor at the start of the current pulse at the end of the battery's life, and V_{MIN} is the circuit operating minimum. V_{MAX} is taken to be 2.698 V assuming an unloaded end of life battery voltage of 2.7 V (V_P).

Based on the power consumption characterization presented in Section 3.2.2.1, this reference design experiences the period of highest current consumption when it is advertising. The load profiles based on this event is shown in Figure 16.

Based on this profile, C1 can be calculated using Equation 8:

$$C1 = \frac{10\ \text{mA} \times 8.32\ \text{ms} - \frac{2.0\ \text{V}}{1\ \text{k}\Omega} \times 8.32\ \text{ms}}{2.698\ \text{V} - 2.0\ \text{V}} = 95.35\ \mu\text{F} \quad (8)$$

This design uses C1 = 100 µF and additional decades of capacitors in parallel for improved impedance at higher frequencies.

2.4.3 Wireless Network Design

This design leverages TI's Bluetooth low energy stack to implement a Bluetooth connection over which data is sent.

The wireless subsystem (CC1350) is configured for 100-ms advertisement and connection intervals. These intervals may be configured to longer periods through software. Each connection interval enables communication of 20 bytes of data.

The firmware for this reference design connects to a central device to transmit sample and FFT data over Bluetooth low energy. The central device can then be used to tell the reference design to return to its low-power standby mode.

The antenna on this reference design is the inverted F printed circuit board (PCB) antenna for 2.4-GHz transceivers and transmitters. See the 2.4-GHz Inverted F Antenna application note (SWRU120) for more details about layout and performance.

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2.4.4 Firmware Control

Figure 6 describes the firmware operation in this reference design.

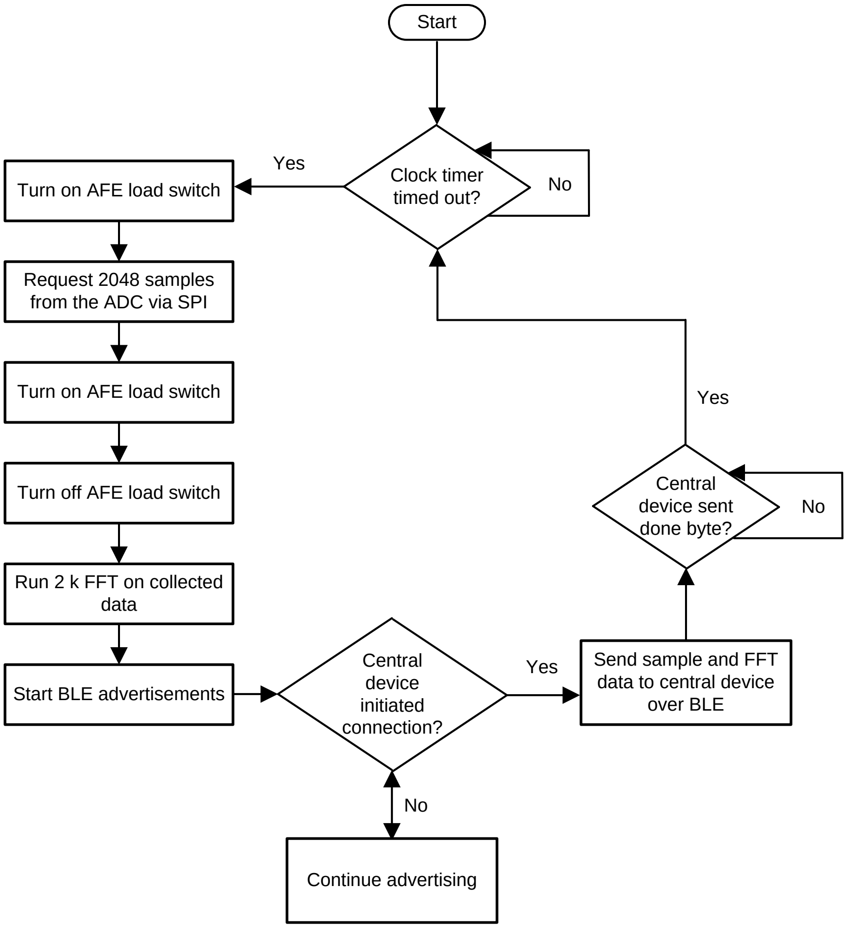

Figure 6. Firmware Flow Chart

For this design, a wakeup interval of 8 hours was used. The RTC on the CC1350 was used to keep track of the wakeup interval. By powering on the load switch only when data was being sampled by the ADC and sent to the MCU, power was conserved. Data was sent out in a connection (as opposed to just using advertising packets) due to the large amount of data that is being transmitted.

The task priority for the task containing the code for sampling from the ADC is currently set to a priority of 2. A higher number represents a high priority task. This is to prevent it from interfering with any tasks that are essential to the Bluetooth low energy operation, but it may need to be raised if any other tasks are added that could possibly preempt the sampling from the ADC. The highest priority task that is ready to run at any point will be run.

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3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

The motor monitoring reference design uses the following hardware:

- TIDA-01469 PCB (sensor board)
- CC1350 LaunchPad (LAUNCHXL-CC1350)
- CR2032 Coin cell battery
- CC13xx or CC26xx (CC1350, CC2650, CC2640, CC2640R2) device that can be used with the BTool PC tool (a LaunchPad or SmartRF06 board must be used)

This reference design includes the pre-built images needed for evaluation. For modifying, debugging, and rebuilding custom images the following software is needed:

- TI's Code Composer Studio (CCS) version 7.1.0
- BLE stack v 2.2.1
- Flash Programmer 2
- BTool (available with BLE-stack SDK)

3.1.1 Hardware

Figure 7 shows the hardware for the motor monitoring reference design. The PCB is in a 58.50×95.30-mm rectangular form factor. All the integrated circuits, sensor, test points, jumpers, and battery holder are located on the top side of the PCB. The bottom side of the PCB contains the connectors for the CC1350 LaunchPad.

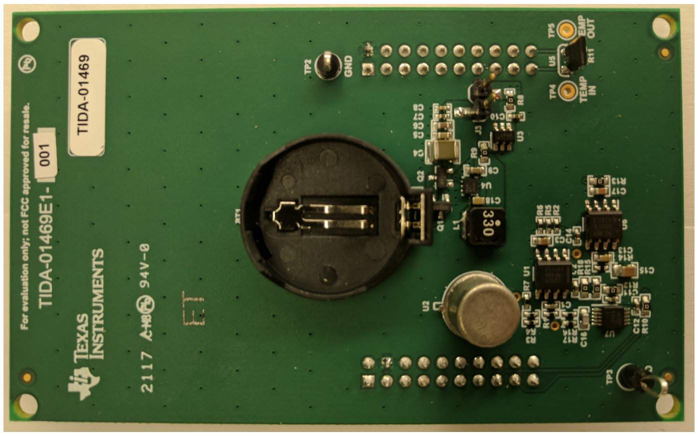

Figure 7. Wireless Vibration Sensor Reference Design Hardware Description

As shown in Figure 8, the reference design PCB is designed to attach directly to the CC1350 LaunchPad (LAUNCHXL-CC1350). The reference design PCB and the CC1350 LaunchPad together make up the sensor node. The assembled system can be powered from the USB port on the CC1350 LaunchPad or from the battery on the PCB. See Section 3.1.1.1 for more details on the jumper configuration for each of these two options.

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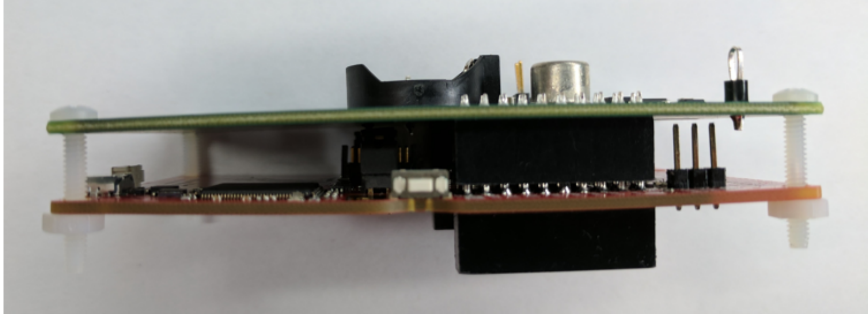

Figure 8. Fully Assembled System

Table 3 lists the assignments of different signals in the reference design PCB to the input/output pins of the CC1350 LaunchPad.

Table 3. Pin Assignments When Used with CC1350 LaunchPad

SIGNAL	PIN ASSIGNMENT
SPI_CLK	DIO10
SPI_CS	DIO21
SPI_SDI	DIO22
LS_INT	DIO19
TEMP_IN	DIO15
TEMP_OUT	DIO8

3.1.1.1 Jumper Configuration

To properly operate the reference design, the jumpers on the design PCB and the CC1350 LaunchPad must be installed correctly.

To power the entire system from the CC1350 LaunchPad and enable the onboard emulator configure the jumpers as follows:

- TIDA-01469 Board J3 = Opened (disconnects battery from system)
- CC1350 LaunchPad P4 = All jumpers on (XDS110 powers CC1350 and TIDA-01469 board, all JTAG signals connected to CC1350)
- CC1350 LaunchPad P10: Set to XDS110 Power (full debug supported)
- (Optional) CC1350 LaunchPad P6: Both jumpers on (enables LEDs)

To power the entire system from the coin cell battery and disable the onboard emulator configure the jumpers as follows:

- TIDA-01469 Board J3 = Jumper on (connects battery to system)
- CC1350 LaunchPad P4 = All jumpers removed (removes XDS power from CC1350 and TIDA-01469 board, disconnects all JTAG signals)
- CC1350 LaunchPad P10: Off (removes power from level shifters, disables debug)
- (Optional) CC1350 LaunchPad P6: Both jumpers removed (disables LEDs)

3.1.1.2 Test Point Description

This reference design includes several test points to monitor critical signals. The following is a brief description of these test points:

- TP2, TP3: Ground points for probes or common points for voltage measurements
- TP4: Temperature sensor input
- TP5: Temperature sensor output

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3.1.1.3 Battery Requirements

Only insert an Energizer™ CR2032VP lithium battery or battery with equivalent specifications:

- CR2032 UL certified battery
- Voltage: 3.0 V
- Minimum capacity: 240 mAh
- Minimum discharge rate: 0.19 mA

NOTE: The battery must be replaced by a trained professional.

3.1.2 Software

3.1.2.1 Compiling Firmware

The firmware for this reference design is developed using TI's CCS software (version 7.1.0), BLE SDK 2.02.01.18, TI-RTOS 2.20.01.08, and ARM Compiler Tools 5.2.6. The instructions in this document detailing how to build the firmware assume that CCS and the software packages have been set up and configured correctly. For more information on how to set up the development environment, consult the *CC2640 BLE Software Developer's Guide* provided in the docs folder of the BLE SDK.

To import the project into CCS:

1. Open CCS.
2. Click on the *Project* toolbar.
3. Select *Import CCS Projects…*
4. Select the radio option *Select archive file*.
5. Navigate to where the TIDA01469_BLE_Peripheral_App.zip file is installed. If using the default location, the firmware is at the location, C:\ti\TIDA01469-Firmware.
6. Verify that the optionTIDA01469_BLE_Peripheral_Stack is checked.
7. Click the *Finish* button.
8. Click on the *Project* toolbar.
9. Select *Import CCS Projects…*
10. Select the radio option *Select search-directory*.
11. Navigate to where the simple_peripheral stack project is located. If using the default location, the firmware is at the location, C:\ti\simplelink\ble_sdk_2_02_01_18\examples\cc1350lp\simple_peripheral\ccs\stack.
12. Verify that the option *simple_peripheral_cc1350lp_stack* is checked.
13. Click the *Finish* button.

At this point, the CCS workspace must have both *simple_peripheral_cc1350lp_app* and *simple_peripheral_cc1350lp_stack* projects.

To build the firmware:

1. Set the simple_peripheral_cc1350lp_stack project as the active project, and build the project using Project → Build Project. The generated binary file, simple_peripheral_cc1350lp_stack.hex, is in the simple_peripheral_cc1350lp_stack/FlashROM folder.
2. Set the simple_peripheral_cc1350lp_app project as the active project, and build the project using Project → Build Project. The generated binary file, simple_peripheral_cc1350lp_app.hex, is in the simple_peripheral_cc1350lp_app/FlashROM folder.

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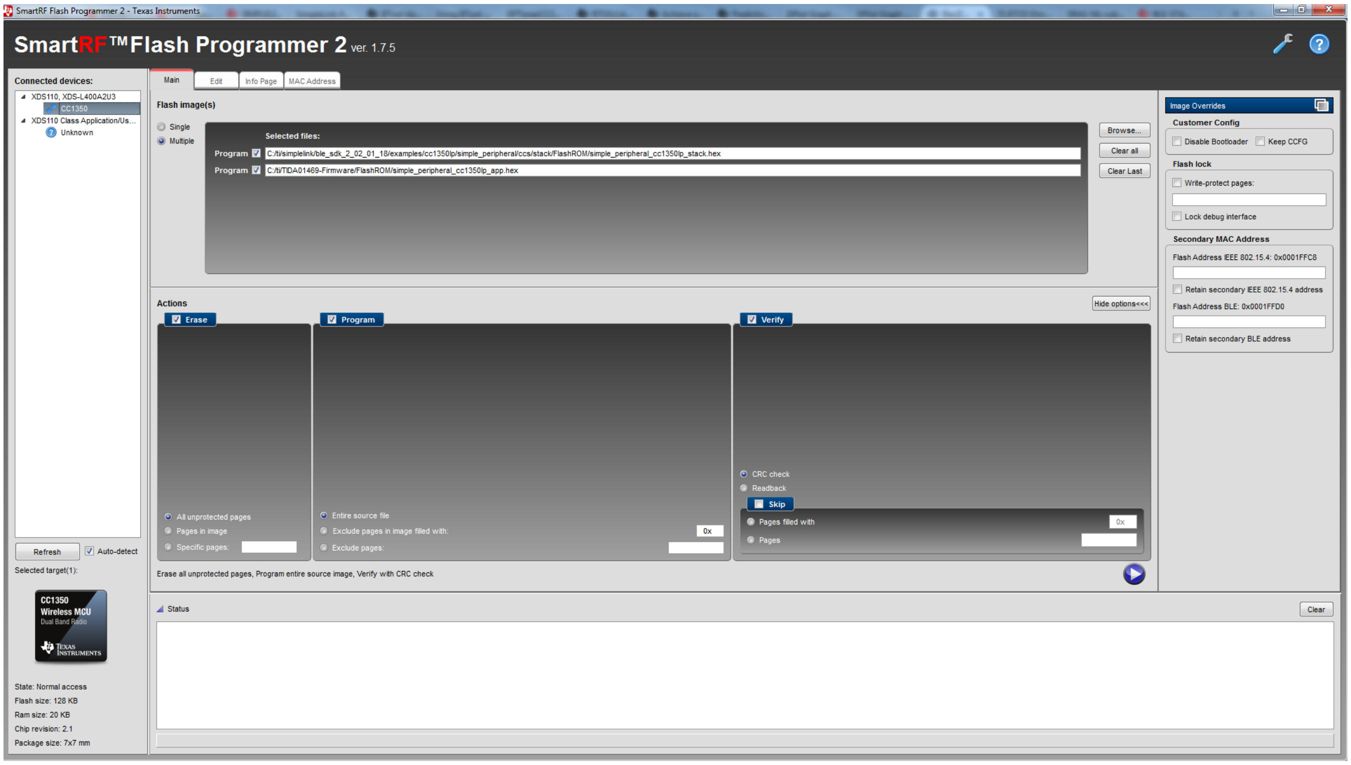
3.1.2.2 Loading Firmware on Wireless MCU Using Binaries

Included in the reference design firmware is a set of pre-built binary images for the application and stack, which can be loaded through the onboard emulator on the CC1350 LaunchPad. Both can be loaded at the same time. Simply configure the jumpers on the CC1350 LaunchPad to enable the onboard emulator (see Section 3.1.1.1) and connect a USB cable to the CC1350 LaunchPad. After setting up all the hardware, follow these steps to load the firmware on the sensor and collector using the SmartRF Flash Programmer 2:

1. Download and install SmartRF Flash Programmer 2 (http://www.ti.com/tool/flash-programmer).
2. Open SmartRF Flash Programmer 2.
3. In the "Connected devices" window, CC1350 must be listed under XDS110. If it is not listed, check the USB connection to the CC1350 LaunchPad and click "Refresh" button to rescan for devices. Highlight the CC1350 device.
4. In the "Main" tab, click the "Multiple" radio button.
5. *IMPORTANT*: In the "Main" tab, under "Actions", click the "All unprotected pages" radio button. This button erases previous network association information.
6. Click on the "Browse" button and navigate to the location of the binary files as described in Section 3.1.2.1 (see Figure 9).



Connected devices:
- XDS110, XDS-L400A2U3
  - CC1350
- XDS110 Class Application/Us...
  - Unknown

Flash image(s)
○ Single
● Multiple

Selected files:
Program ☑ C:/ti/simplelink/ble_sdk_2_02_01_18/examples/cc1350lp/simple_peripheral/ccs/stack/FlashROM/simple_peripheral_cc1350lp_stack.hex
Program ☑ C:/ti/TIDA01469-Firmware/FlashROM/simple_peripheral_cc1350lp_app.hex

Customer Config
☐ Disable Bootloader ☐ Keep CCFG

Flash lock
☐ Write-protect pages:
☐ Lock debug interface

Secondary MAC Address
Flash Address IEEE 802.15.4: 0x0001FFC8
☐ Retain secondary IEEE 802.15.4 address
Flash Address BLE: 0x0001FFD0
☐ Retain secondary BLE address

Actions
☑ Erase
● All unprotected pages
○ Pages in image
○ Specific pages:

☑ Program
● Entire source file
○ Exclude pages in image filled with: 0x
○ Exclude pages:

☑ Verify
● CRC check
○ Readback
☐ Skip
○ Pages filled with 0x
○ Pages

Erase all unprotected pages, Program entire source image, Verify with CRC check

☑ Auto-detect
Selected target(1):

State: Normal access
Flash size: 128 KB
Ram size: 20 KB
Chip revision: 2.1
Package size: 7x7 mm

Figure 9. SmartRF Flash Programmer 2 Configuration

7. Click on the blue circle play button to flash the firmware image onto the sensor. The status bar on the bottom of SmartRF Flash Programmer 2 will show if flashing the image was successful.

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3.1.2.3 Loading Firmware Using CCS

Follow these steps to program with CCS:

1. Download simple_peripheral_cc1350lp_stack by selecting the simple_peripheral_cc1350lp_stack project as the active project, and choosing Run → Debug.
2. Choose Run → Terminate to stop the debug.
3. Download simple_peripheral_cc1350lp_app by selecting the simple_peripheral_cc1350lp_app project as the active project, and choosing Run → Debug.

NOTE: The preceding steps are needed only for the initial download, and whenever the stack project is modified. As long as the stack project is not modified, the only required steps are:

1. Build the application.
2. Download the application.

3.1.2.4 Configuring BTool

Follow these steps to set up BTool to act as a central device and communicate with the reference design:

1. Obtain a CC13xx or CC26xx device that can connect to a computer using a USB cable (either a LaunchPad or a SmartRF board) and can run TI's BLE SDK.
2. Plug the device into a computer using the provided USB cable.
3. Flash the device with the *host_test* project, found in the *Examples* folder of the SDK.
4. Run BTool, which can be found in the *Tools* folder of the SDK.
5. In BTool, connect to the correct port corresponding to the device that is connected through USB.

A more detailed description of using BTool can be found in the BTool User's Guide

NOTE: This design guide is written specifically for the CC2640R2 LaunchPad, but very similar steps are required to use other platforms.

3.1.2.5 Running the Firmware

To gather motor data, process it, and send it out over a Bluetooth low energy connection, follow these steps:

1. Disconnect all jumpers from the CC1350 LaunchPad. This prevents the debugging and power interface of the board from unnecessarily drawing high current when the reference design is running on a coin cell battery. See Section 3.1.1.1 for details.
2. Attach the CC1350 LaunchPad to the TIDA-01469 board using four screws and four hex nuts and the mounting holes in each corner of both boards. The following parts are used to test this design:
   - NY PMS 440 0075 PH
   - NY HN 440

   Before using the screws, make sure that the boards are correctly connected using the pin connectors.
3. Make sure that a coin cell battery has been inserted into the battery holder. Do not connect the J3 jumper on the design board until the program is ready to start.
4. Attach a small magnet to the battery. This magnet couples the reference design to the motor to accurately detect the vibrations in the motor.
5. Connect the J3 jumper on the design board, and use the magnet to attach the reference design to the motor.
6. The program will now begin. For demo purposes, the reference design wakes up after 5 seconds to take measurements, process the data, and begin sending out Bluetooth low energy advertisements. Every time the reference design goes back into standby, this wake-up interval is the amount of time after which the design will wake up to sample data and take the FFT. The code also has an option for a wake-up interval of 8 hours, and any other value can be chosen.

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7. Once the device is advertising, the device running BTool can be used to connect to the reference design. Follow the BTool User's Guide described in Section 3.1.2.4 for detailed instructions on how to do this.
8. Once connected, BTool can be used to request the desired data from the reference design. Table 4 shows what values to write to characteristic 1 to request each block of sample and FFT data.

Table 4. Values for Requesting Data

CHARACTERISTIC 1 VALUE	DATA TO REQUEST
5D	200 sampled data points
5E	First 200 FFT points
5C	Second 200 FFT points
5B	Third 200 FFT points
5A	Fourth 200 FFT points
59	Fifth 200 FFT points

9. Once notifications have been enabled for characteristic 5 (by writing a value of 1 to characteristic 5's Client Characteristic Configuration Descriptor), each group of 200 points will be sent to the device running BTool in groups of 20 notifications. The BTool User's Guide describes this process.
10. To tell the design board to go back to standby and wait for the next time to sample data, use BTool to write any non-zero value to characteristic 3.

3.2 Testing and Results

3.2.1 Test Setup

The Motor Monitoring Using Wireless Vibration Sensor Reference Design has been characterized to support all of the critical specifications for this subsystem. The following sections describe the test setup for these measurements, including the equipment used and the test conditions unless otherwise noted.

3.2.1.1 Power Consumption

The power consumption measurements for this reference design are critical in estimating battery life. Measurements of supply current are performed on the reference design hardware.

The majority of the time, the system operates in a very low-power consumption state, often only consuming microamps of current. The test setup for measuring these small currents is illustrated in Figure 10.

The resolution setting of the Agilent 34410A 6½ digit multimeter can place a limit on the amount of instantaneous current flowing to the device under test (DUT). This limit can become a problem because at different points during normal operation the current jumps from the microamp range to the milliamp range. For example, when powering on the board, there is an initial inrush of current to the board. Generally, a resolution of 10 mA is enough to prevent any issues with current limits.

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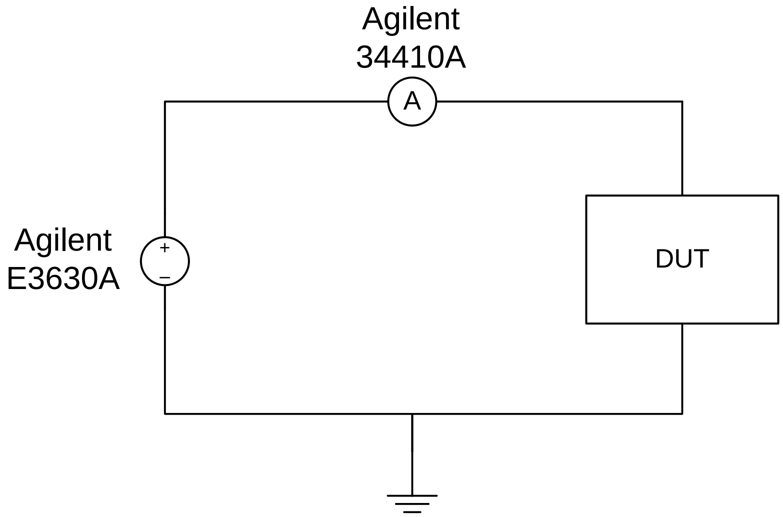

Figure 10. Test Circuit Used for Measuring Small Currents

The system also experiences peaks of high current such as those generated during radio transmission. Measuring these intervals involves using a voltage probe that interfaces to an oscilloscope, which can then be used to trigger on the high current events. The voltage is measured across a small sense resistor, which allows the current to be calculated. This setup is illustrated in Figure 11.

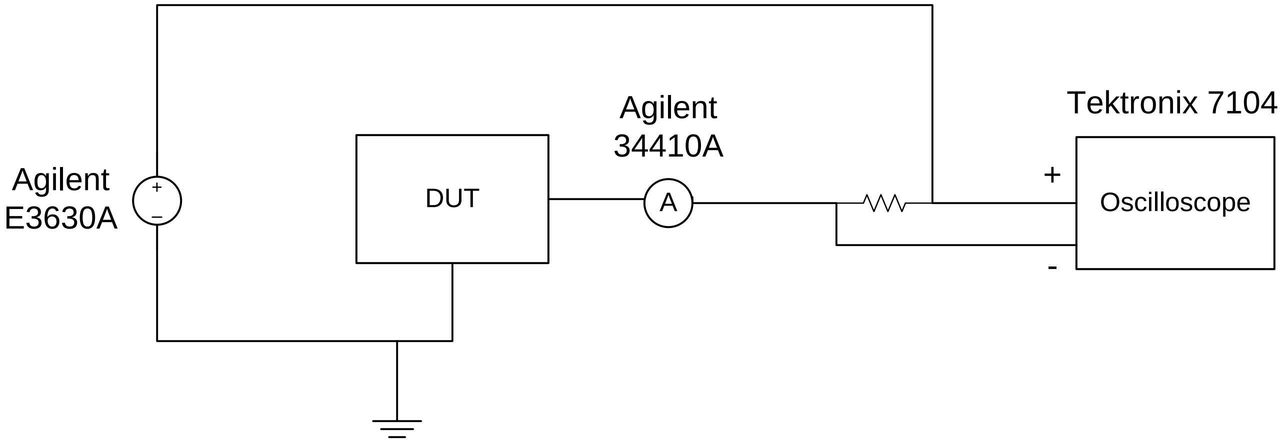

Figure 11. Test Circuit Used for Measuring Supply Current During High-Peak Currents

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3.2.1.2 Signal Chain Testing

The accelerometer is taken off of this design board so that a function generator could be used to give a known sine wave input to the AFE. This setup is shown in Figure 12. This test shows that the AFE provides the correct amplified signal to the ADC, and that the ADC and MCU properly samples the signal and take the FFT. An offset of 1.7 V is used with the function generator to match the reference voltage that was provided to the accelerometer. An amplitude of 20 mV is used, and the frequency is varied throughout the range of the reference design (50 Hz to 10 kHz). Because of the output limitations of the function generator, a voltage divider is used to get a signal amplitude that is low enough to prevent attenuation of the amplified signal.

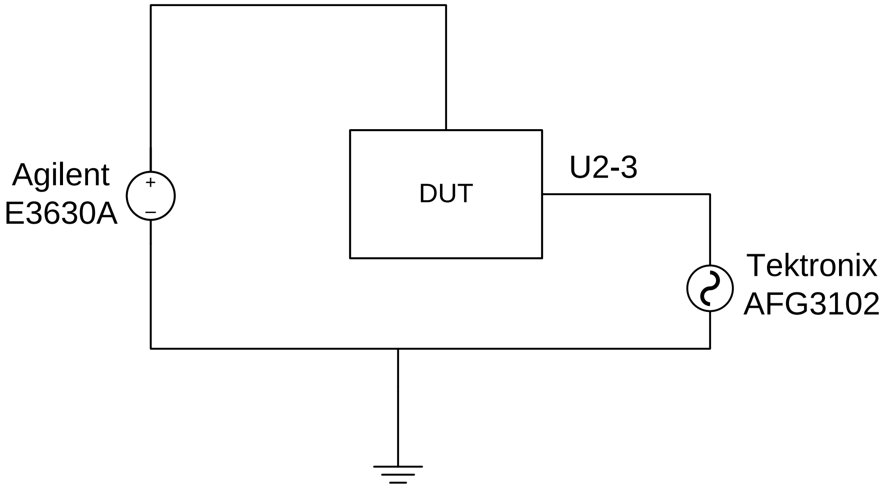

Figure 12. Setup With Accelerometer Replaced by Function Generator

3.2.1.3 Motor Vibration Sensing

An actual industrial motor is used to get motor vibration test data. As described in Section 3.1.2.5, a magnet attached to the battery on the design board couples the reference design to the motor. Figure 13 shows the motor, and Figure 14 shows how the reference design is attached to it. Sample and FFT data are then obtained as described in Section 3.1.2.5.

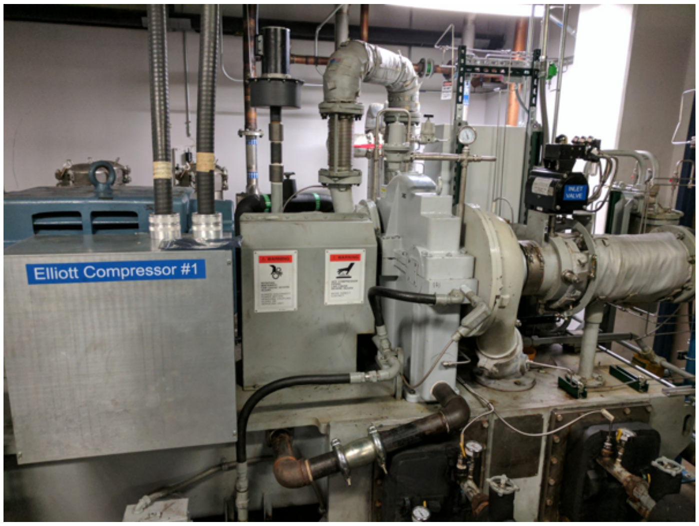

Figure 13. Motor Setup

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Figure 14. Reference Design Coupled to Motor

3.2.1.4 Wireless Range

The range of the wireless 2.4-GHz Bluetooth low energy transmission is measured using one CC1350 LaunchPad (as part of the reference design) and a Google Pixel with the BLE Scanner app. The reference design is set to send out advertisement packets with 100-ms advertising intervals. The phone is then moved further away from the reference design and checked to see if the reference design could still be seen advertising. The phone is always in direct sight of the reference design. The distance at which packets are no longer received are then measured.

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3.2.2 Test Results

NOTE: Unless otherwise noted, the test data in the following sections are measured with the system at room temperature. All of the measurements in this section are measured with calibrated lab equipment.

3.2.2.1 Power Characterization

Because the primary purpose of this reference design is to showcase a battery-powered wireless sensor, characterization of the power consumption of the system is critical.

This reference design remains primarily in the standby state, which is the default state. It is critical that the power consumption of this state remain as low as possible such that the battery life of the system can be maximized. In this state, the CC1350 receives power, but will go into its standby mode to minimize power consumption. The TPS22860 load switch is turned off to cut off power completely to the op amp, ADC, VREF, and boost converter in the analog input stage.

Table 5 shows the average current consumption of the entire system when it is operating in the standby mode. The current consumption is characterized across different battery voltages. As expected, the current consumption increases at the lower voltage ranges because the internal DC-DC of the CC1350 must recharge the bypass capacitors more often to maintain a constant supply voltage. For battery life calculations, the average current is calculated over the range of battery voltages from 2.4 to 3.6 V. The average current for standby mode in these voltage ranges is 879.5 nA.

Table 5. Average Current Consumption Across Battery Voltage in Standby Mode

VBATT (V)	AVERAGE SYSTEM CURRENT (nA)
3.6	801
3.3	832
3.0	853
2.8	885
2.6	932
2.4	974

In addition to the standby state, this reference design consumes varying amounts of power when it is acquiring samples from the ADC, applying the FFT to these samples, sending out Bluetooth low energy advertisements, and sending out data over a Bluetooth low energy connection. A small sense resistor is used to measure the small amount of current being drawn by the system during each of these periods, and this was confirmed using a digital multimeter. This process is described in Section 3.2.1.1.

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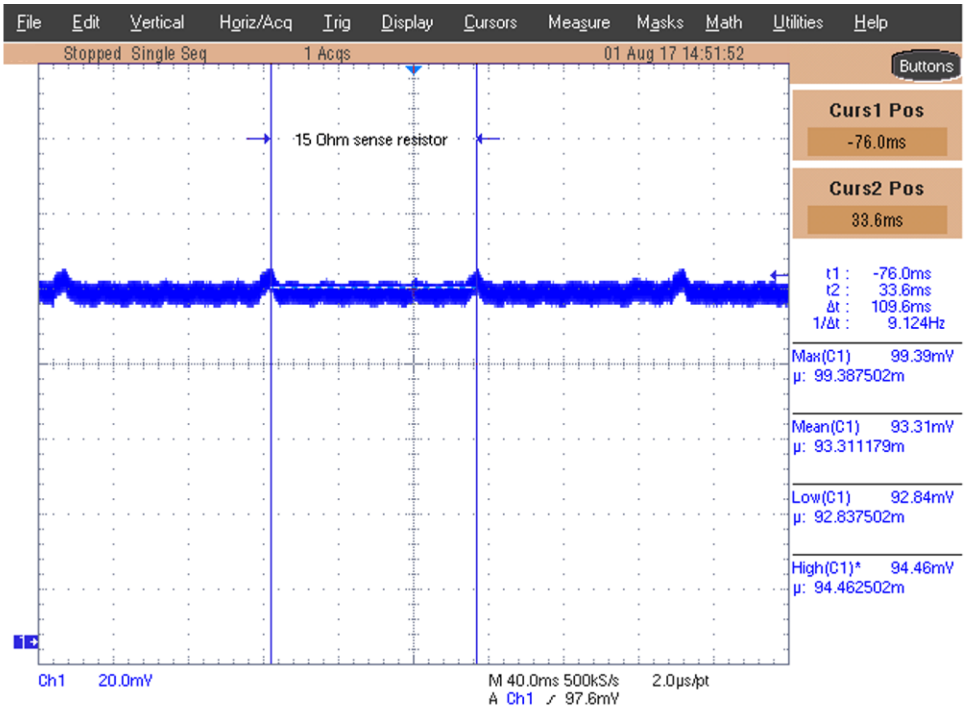
The first state of this reference design after it exits standby mode is sampling data from the ADC through SPI and performing an FFT on this data. Figure 15 shows the power characterization of the design during this state.



Stopped Single Seq 1 Acqs 01 Aug 17 14:51:52

Curs1 Pos -76.0ms

Curs2 Pos 33.6ms

t1 : -76.0ms
t2 : 33.6ms
Δt : 109.6ms
1/Δt : 9.124Hz

Max(C1) 99.39mV
μ: 99.387502m

Mean(C1) 93.31mV
μ: 93.311179m

Low(C1) 92.84mV
μ: 92.837502m

High(C1)* 94.46mV
μ: 94.462502m

Ch1 20.0mV

M 40.0ms 500kS/s 2.0μs/pt
A Ch1 ⁄ 97.6mV

Figure 15. ADC Sampling and FFT Power Characterization

The average voltage is 93.31 mV, so dividing by the resistance of the sense resistor gives an average current of 6.221 mA. This average current is over a period of approximately 109.6 ms. The larger pulses correspond to the FFT, and the smaller pulses in between correspond to the ADC sampling through SPI. Only one period is actually performed by this design each time that it wakes up to take data. A loop is used around the ADC sampling and FFT to make it easier to visualize.

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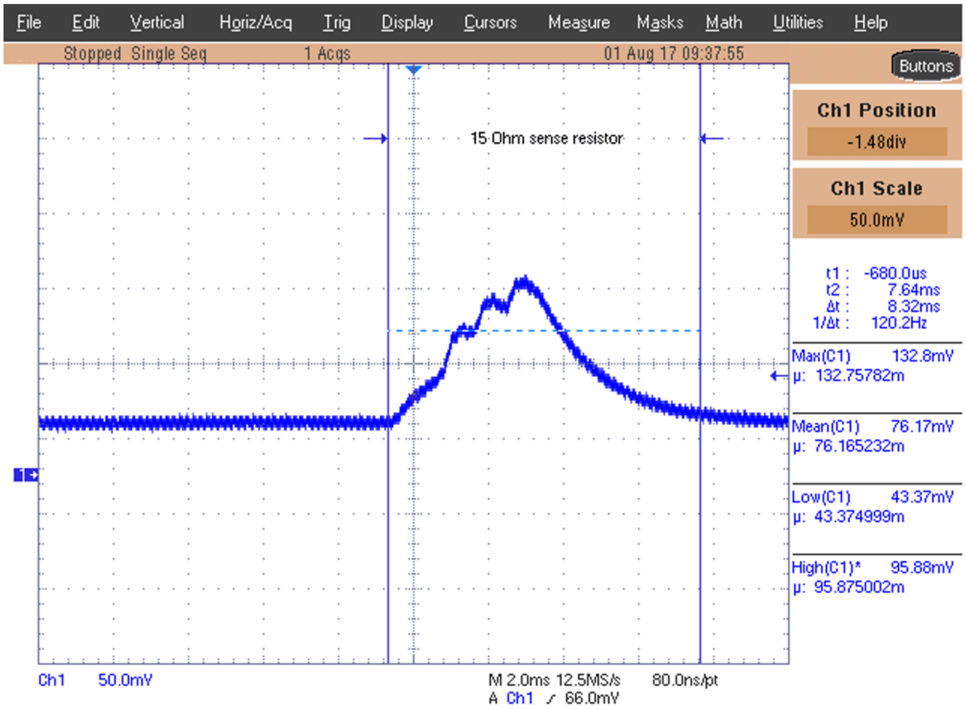
Figure 16 shows the equivalent current waveform for a Bluetooth low energy advertisement. The voltage readings are averaged over the time of the packet pulse time and a 15-Ω sense resistor is used.



Stopped Single Seq 1 Acqs 01 Aug 17 09:37:55

Ch1 Position -1.48div

Ch1 Scale 50.0mV

t1 : -680.0us
t2 : 7.64ms
Δt : 8.32ms
1/Δt : 120.2Hz

Max(C1) 132.8mV
µ: 132.75782m

Mean(C1) 76.17mV
µ: 76.165232m

Low(C1) 43.37mV
µ: 43.374999m

High(C1)* 95.88mV
µ: 95.875002m

Ch1 50.0mV M 2.0ms 12.5MS/s 80.0ns/pt
A Ch1 ⁄ 66.0mV

Figure 16. Advertising Packet Power Characterization

The average voltage is 76.17 mV, so dividing by the resistance of the sense resistor gives an average current of 5.078 mA. This average current is over a pulse width of approximately 8.32 ms.

This reference design sends out advertisement packets every 100 ms, as shown in Figure 17. The tiny pulses seen between the advertising packet transmissions are the internal DC-DC converter of the CC1350 charging up for the next transmission.

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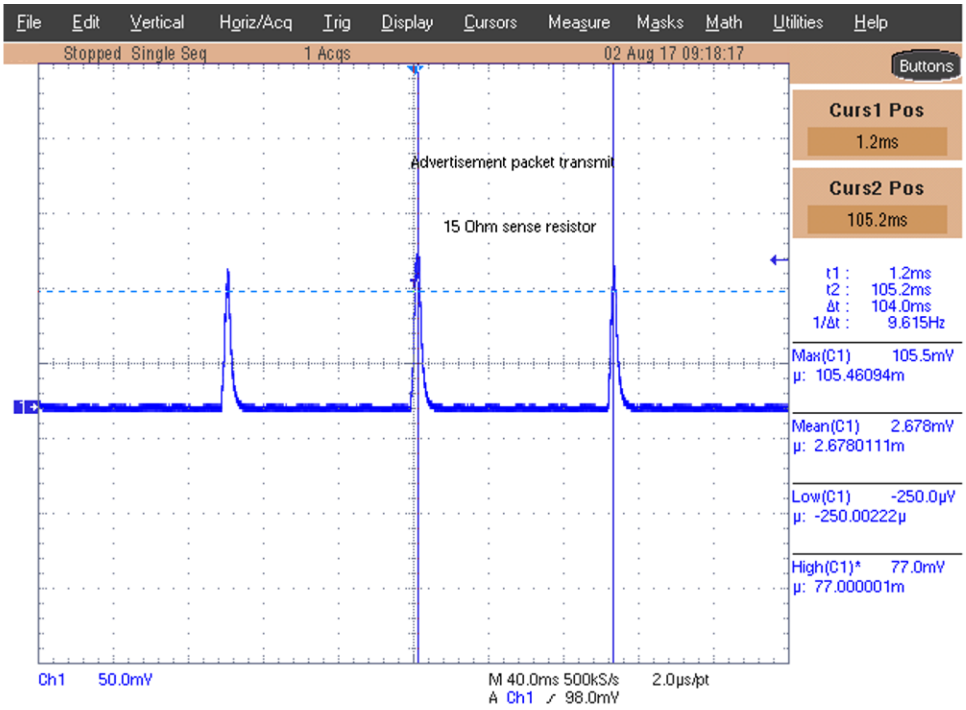


Stopped Single Seq 1 Acqs 02 Aug 17 09:18:17

Curs1 Pos 1.2ms

Curs2 Pos 105.2ms

t1 : 1.2ms
t2 : 105.2ms
Δt : 104.0ms
1/Δt : 9.615Hz

Max(C1) 105.5mV
µ: 105.46094m

Mean(C1) 2.678mV
µ: 2.6780111m

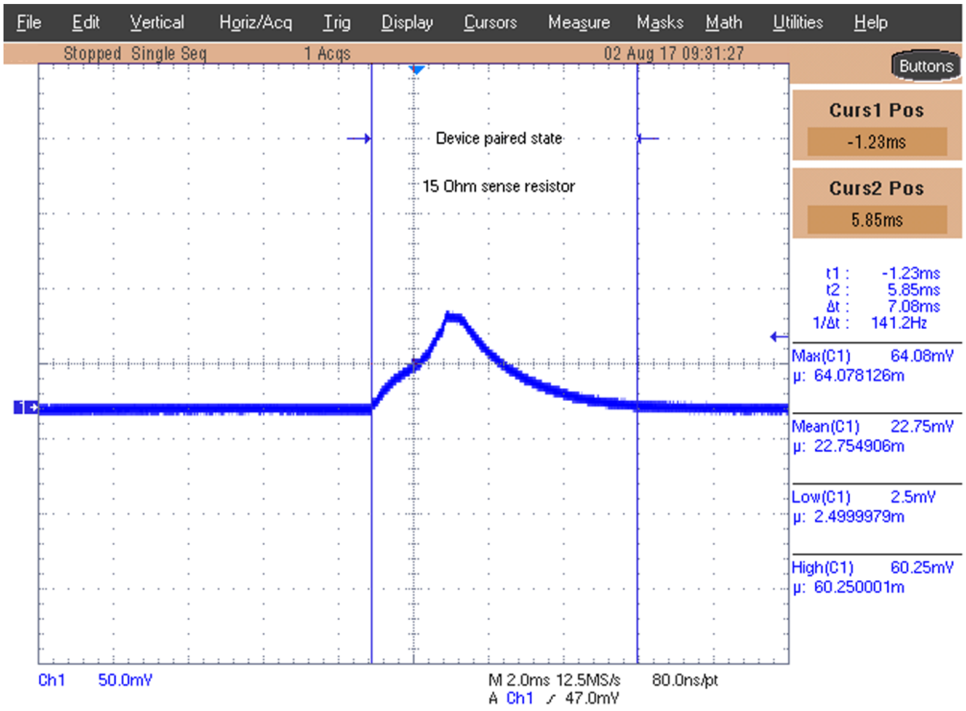
Low(C1) -250.0µV
µ: -250.00222µ

High(C1)* 77.0mV
µ: 77.000001m

M 40.0ms 500kS/s 2.0µs/pt
A Ch1 ⟋ 98.0mV

Figure 17. Advertisement Transmit Period

Once the device connects to another Bluetooth low energy device, the current consumption looks slightly different. Figure 18 shows what the waveform looks like for each connected pulse. These connection events are sent to maintain the connection. The maximum voltage is slightly lower than that of the advertisement packets, and the pulse length is shorter.



Stopped Single Seq 1 Acqs 02 Aug 17 09:31:27

Curs1 Pos -1.23ms

Curs2 Pos 5.85ms

t1 : -1.23ms
t2 : 5.85ms
Δt : 7.08ms
1/Δt : 141.2Hz

Max(C1) 64.08mV
µ: 64.078126m

Mean(C1) 22.75mV
µ: 22.754906m

Low(C1) 2.5mV
µ: 2.4999979m

High(C1) 60.25mV
µ: 60.250001m

M 2.0ms 12.5MS/s 80.0ns/pt
A Ch1 ⟋ 47.0mV

Figure 18. Connection Packet Power Characterization

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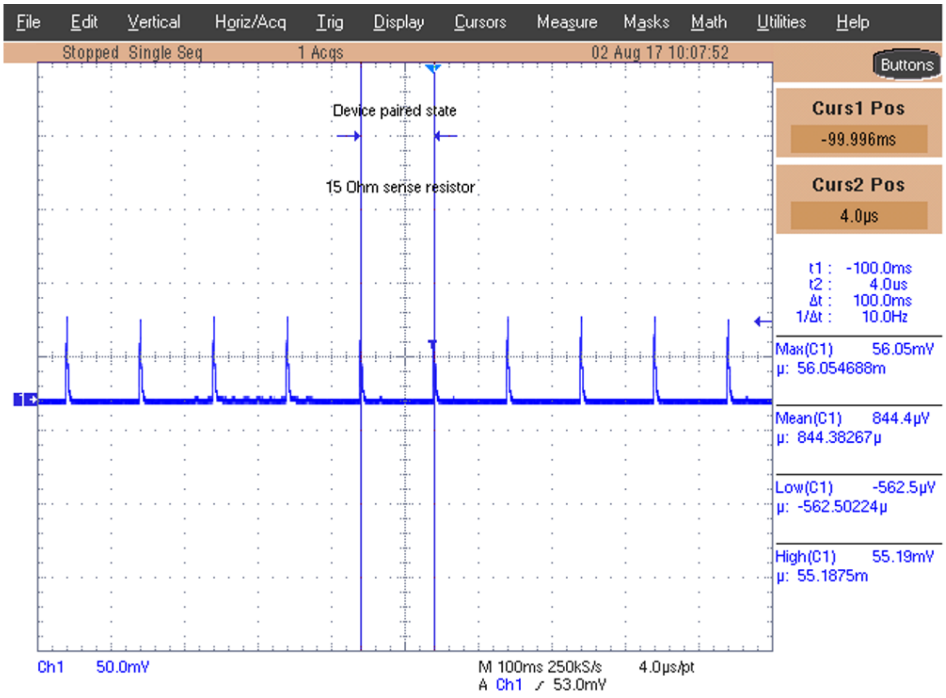
The average voltage is 22.755 mV, so dividing by the resistance of the sense resistor gives an average current of 1.517 mA. This average current is over a pulse width of approximately 7.08 ms. Figure 19 shows the period of the device when it is in a connection. The connection interval is 100 ms.



Stopped Single Seq 1 Acqs 02 Aug 17 10:07:52

Curs1 Pos -99.996ms

Curs2 Pos 4.0µs

t1 : -100.0ms
t2 : 4.0us
Δt : 100.0ms
1/Δt : 10.0Hz

Max(C1) 56.05mV
µ: 56.054688m

Mean(C1) 844.4µV
µ: 844.38267µ

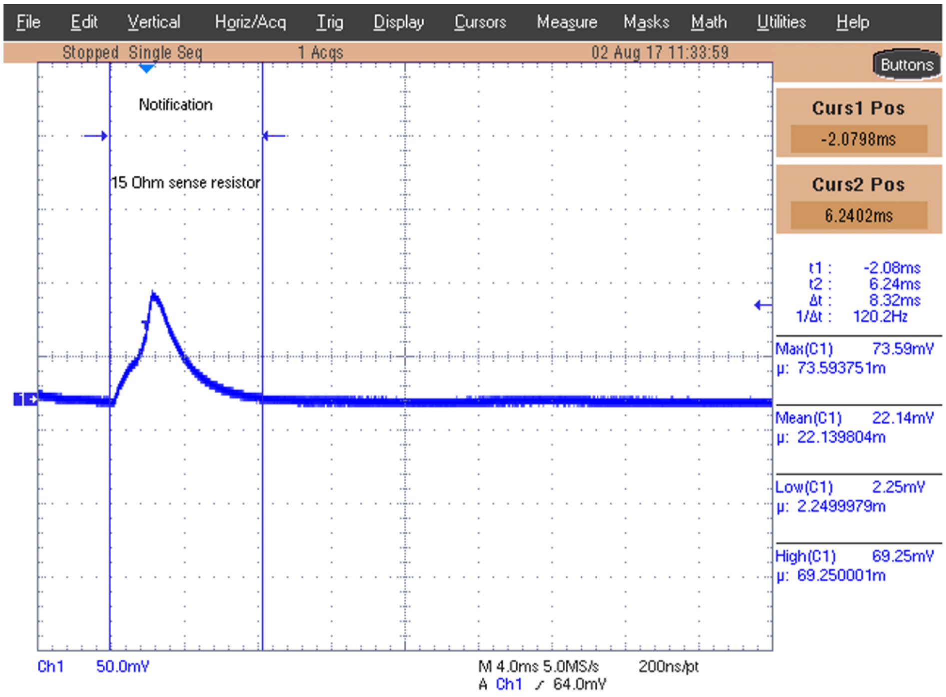
Low(C1) -562.5µV
µ: -562.50224µ

High(C1) 55.19mV
µ: 55.1875m

Ch1 50.0mV M 100ms 250kS/s 4.0µs/pt
A Ch1 ⁄ 53.0mV

Figure 19. Connection Packet Transmit Period

Figure 20 shows the power characterization of notification pulse. Each pulse corresponds to the transmission of 20 bytes of data in a single notification.



Stopped Single Seq 1 Acqs 02 Aug 17 11:33:59

Curs1 Pos -2.0798ms

Curs2 Pos 6.2402ms

t1 : -2.08ms
t2 : 6.24ms
Δt : 8.32ms
1/Δt : 120.2Hz

Max(C1) 73.59mV
µ: 73.593751m

Mean(C1) 22.14mV
µ: 22.139804m

Low(C1) 2.25mV
µ: 2.2499979m

High(C1) 69.25mV
µ: 69.250001m

Ch1 50.0mV M 4.0ms 5.0MS/s 200ns/pt
A Ch1 ⁄ 64.0mV

Figure 20. Notification Power Characterization

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For BTool to be able to process the notifications before filling its buffer, a delay is required between each notifications. A 20-ms delay is used, so one of these pulses are seen every 20 ms, meaning there are five pulses for each connection period.

3.2.2.2 Battery Life Calculations

The main parameters that affect the estimated battery life of the entire system are:

- Capacity rating of the battery
- Average standby-state current consumption
- Standby-state duration
- Average sampling and FFT current consumption
- Sampling and FFT duration
- Average advertising packet current consumption
- Advertising duration
- Average connection and data transmission current consumption
- Connection and data transmission duration

Equation 9 describes the estimated battery life of the system.

$$\text{Battery Lifetime}\left(\text{yr}\right)=\frac{\text{Battery Capacity}\left(\text{mAh}\right)}{\left(\frac{I_{\text{Standby}}{}^{(\text{mA})}\times t_{\text{Standby}}{}^{(\text{s})}\times I_{\text{Sampling}}+\text{FFT}^{(\text{mA})}\times t_{\text{Sampling}}+\text{FFT}^{(\text{s})}+I_{\text{Advertising}}{}^{(\text{mA})}\times t_{\text{Advertising}}{}^{(\text{s})}I_{\text{Data}}{}^{(\text{mA})}\times t_{\text{Data}}{}^{(\text{s})}}{t_{\text{Total}}{}^{(\text{s})}}\right)}\times\frac{1\text{ year}}{8760\text{ hours}}\times\text{Derating Factor} \tag{9}$$

Because this design involves a connection being established between two devices and data being sent over that connection, the exact timing with which the connection is established and data is requested affects exactly how long the reference design operates in each power consumption state. For the battery calculations of the device, the following assumptions are made:

- An 8-hour interval is used between wakeup events. This interval is the amount of time that the reference design is in standby mode before waking up to sample data.
- A connection is established after one advertisement packet is received by the central device.
- 1000 points of FFT data are sent in five groups that each consisted of 20 10-sample notifications.
- After receiving all of the data, the central device immediately sends a byte to the reference design, indicating that the design must go back into standby mode and wait for the next wakeup event.

With these assumptions considered, Equation 9 can be used to calculate the battery life as 25.112 years.

Table 6 and Figure 21 show the battery life estimates for wakeup intervals ranging from 8 hours down to 10 minutes. This is important because, although larger intervals are more useful for low-power periodic monitoring, a smaller interval may be desired when a motor is showing minor signs of damage so that more frequent monitoring can detect when the damage warrants maintenance.

Table 6. Battery Lifetime versus Wakeup Period

WAKEUP PERIOD (MIN)	BATTERY LIFE (YEARS)
480	25.112064790
240	23.248417910
120	20.244317780
60	16.088422360
30	11.408638870
20	8.840325148
10	5.281879421

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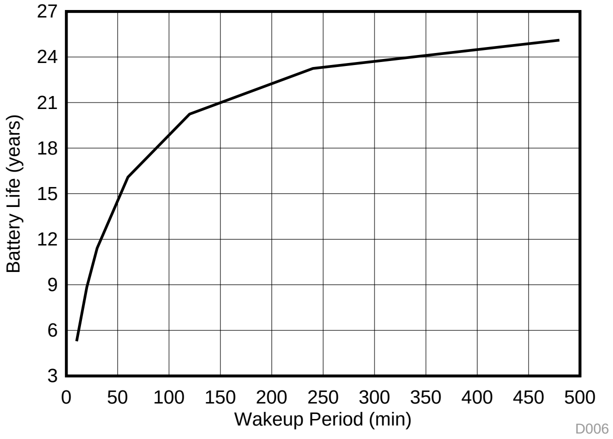

Figure 21. Battery Lifetime versus Wakeup Period

3.2.2.3 *Signal Chain Testing*

As described in Section 3.2.1.2, a function generator is used to give a know signal to the reference design to sample and take the FFT of. Figure 22 shows the data that was sampled and sent out over Bluetooth low energy for a 1-kHz sine wave.

Figure 23 shows the FFT of the data that is sampled from the 1-kHz sine wave.

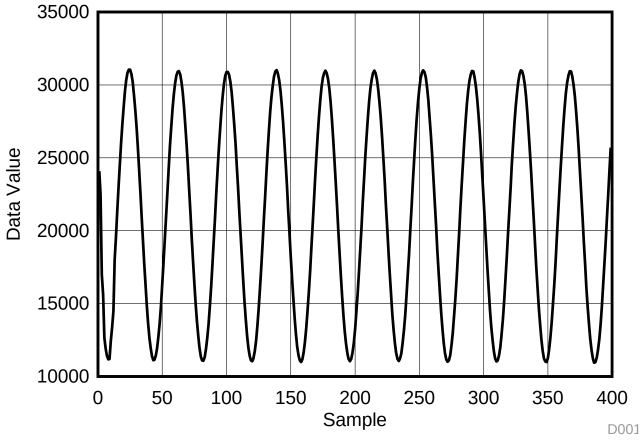

Figure 22. Sampled Data for 1-kHz Sine Wave

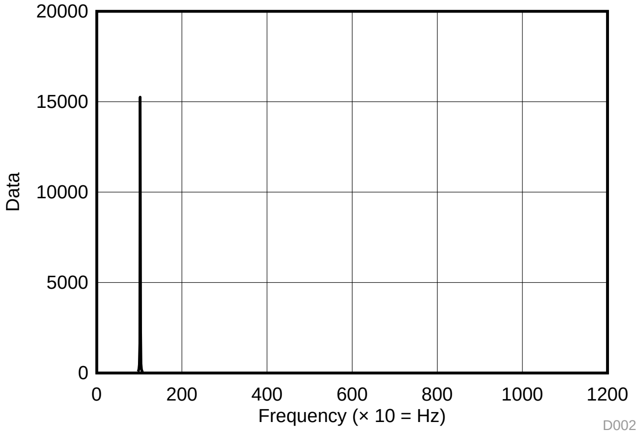

Figure 23. FFT of Data Sampled From 1-kHz Sine Wave

Because a 2K FFT was taken, there are 1000 unique points. For a 20-kHz sampling frequency, each point on the x-axis corresponds to 10 Hz. So, for a 1-kHz sine wave, expect to see an FFT peak at 100. This peak is shown to be the case in Figure 23, thus confirming the accuracy of the FFT calculations as well as the data sampling.

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This process is repeated for a 5-kHz sine wave. The results are shown in Figure 24 and Figure 25.

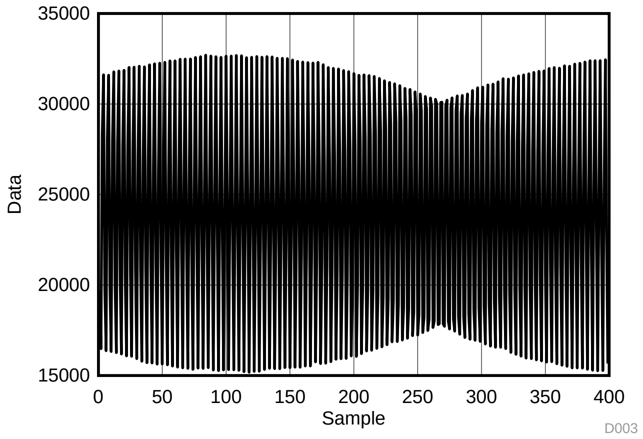

Figure 24. Sampled Data for 5-kHz Sine Wave

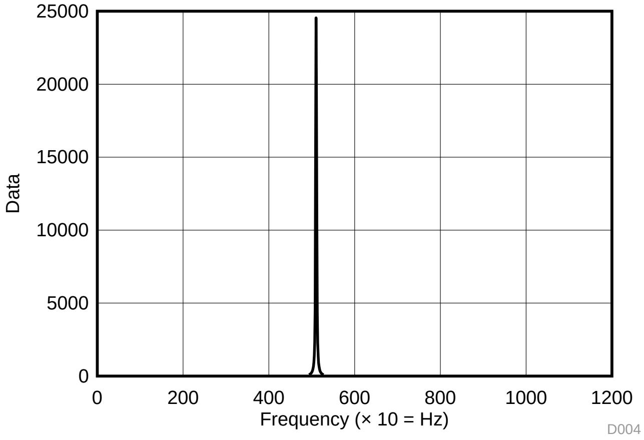

Figure 25. FFT of Data Sampled From 5-kHz Sine Wave

As described for the 1-kHz sine wave, each point on the x-axis for the FFT corresponds to 10 Hz, so expect to see a peak at 500. This is the case here, again confirming the accuracy of the sampling and FFT calculation. The sampled data plot shows less resolution than it did for the 1-kHz sine wave because the signal frequency is closer to the sampling frequency, but the FFT is still able to identify the frequency correctly.

3.2.2.4 Motor Vibration Sensing

The sampled data from the motor setup is shown in Figure 26.

The periodicity of the data can be seen. Because of the multiple present frequencies, only 400 points are shown to increase readability. The FFT generated from this data is shown in Figure 27.

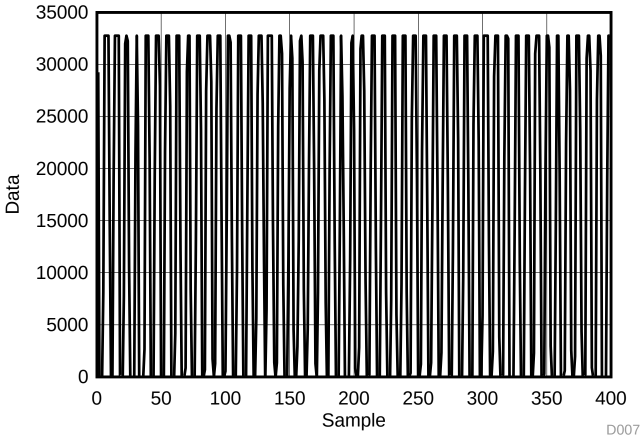

Figure 26. Motor Setup Sampled Data

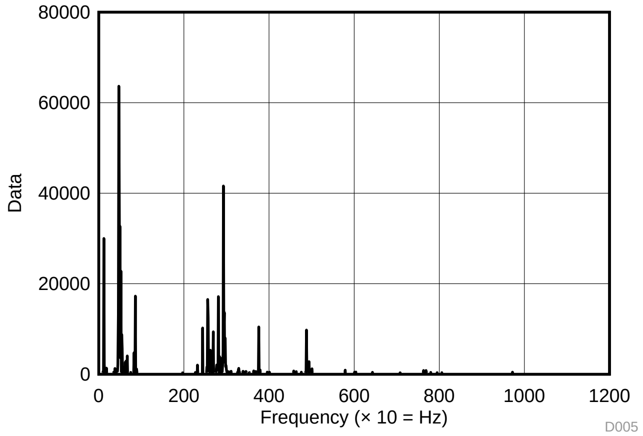

Figure 27. FFT From Motor Setup Sampled Data

Multiple FFT peaks can be seen, which correspond to the multiple harmonics that are present in an actual motor setup. Spectral data generated by the software that is driving the motor is compared to this FFT data to confirm the accuracy of the reference design's sampling and FFT calculation.

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3.2.2.5 Wireless RF Range

The wireless RF range is measured to be about 72 meters in a typical office environment with a direct line of sight. The transmit power is set to 0 dBm, which is the default used by the Bluetooth low energy SDK. Radio performance varies in the end-equipment environment because of the number of obstructions in the RF transmit path reduces range. For full verification of the hardware transmitting characteristics of this reference design, further testing with end-equipment context is required.

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4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-01469.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01469.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01469.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-01469.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01469.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01469.

5 Software Files

To download the software files, see the design files at TIDA-01469.

6 Related Documentation

1. Texas Instruments, *Reverse Current/Battery Protection Circuits*, Application Report (SLVA139)
2. Texas Instruments, *Coin cells and peak current draw*, White Paper (SWRA349)

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7 About the Authors

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