TI Designs
Wireless Motor Monitor (WMM) Design Guide

TI Designs

TI Designs provide the foundation that you need including methodology, testing and design files to quickly evaluate and customize the system. TI Designs help *you* accelerate your time to market.

Design Resources

TIDM-WLMOTORMONITOR	Tool Folder Containing Design Files
MSP430FR5969	Product Folder
CC2650	Product Folder
BQ25570	Product Folder
TPL5100	Product Folder

TI E2E™ Community

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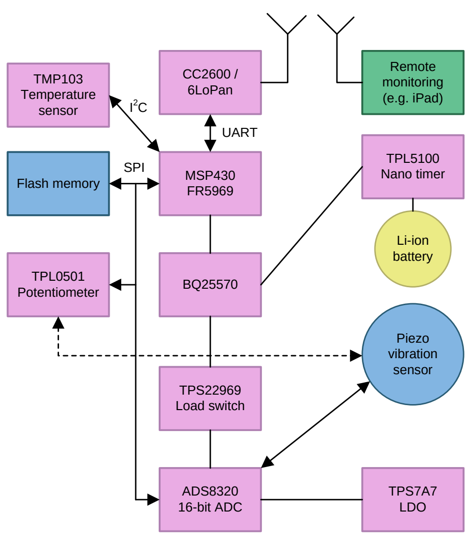
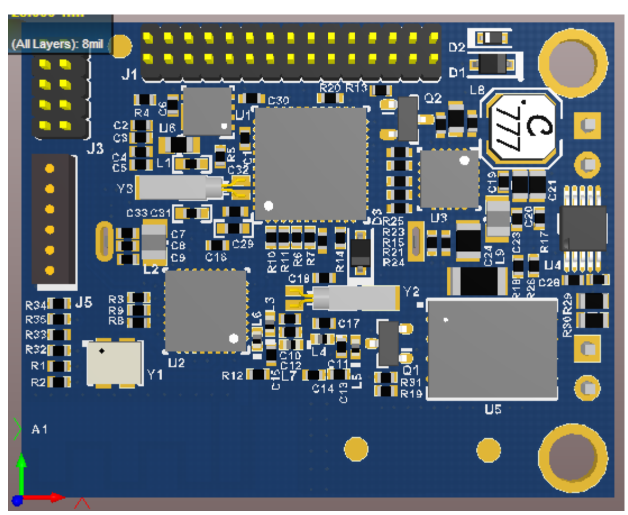
Design Features

- Offers Mechanical Vibration (10 to 50 ksps) and Temperature Sensing.
- Incorporates 4-K FFT for Vibration Spectral Analysis
- Is Optimized for Ultralow Sleep-Mode Current: I_Q < 45-nA (Typical) [BQ-Harvester in Smart Mode]
- Offers Key Parameter Data Logging in FRAM and/or Flash
- Offers Programmable Wake-up Intervals for Motor Diagnostics
- Offers Wireless Connectivity Over Ultralow Power 2.4 GHz BLE or 6LoPAN Networks
- Offers High-Efficiency Power Management and Energy Harvesting for Solar/TEG V_{IN} ≥ 80 mV (Typical)

Featured Applications

- Remote Motor Health Monitoring
  - Intermittent + Long Term
  - Real-Time Mode
- Wireless Machine Monitoring
- Structural Monitoring





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Key System Specifications

Table 1. Key System Specifications

KEY PARAMETERS	SPECIFICATION	DETAILS
Sleep Current	<40 nA	Section 7.4
MSP430 Active Current	<100 µA/mHz	Section 7.4
MSP430 FRAM Current	<100 µA	Section 7.4
CC2650 Rx/Tx	<6 mA	Section 7.2
CC2650 Active Current	<800 µA	Section 7.2
ADS8320 or MSP430 Sampling	16 bit 100 kHz/12 bit 20 kHz	Section 7.3
Piezo Sensor Bandwidth	10 kHz	
Fourier Transform	4000 points	Section 7.1
Operating Voltage	4.2 V to 1.8 V	
Operating Temperature	–30°C to 85°C	
Antenna	Meandered F/SMA	
Default Connection Interval	100 ms	Section 7.2
iOS™ Android™ Graphing	400 points per every few seconds refresh	Section 7.1
Packaging	3D printable hermetic	Section 7.1
Sleep Period	16 seconds to 10 years	
BQ25570 Harvesting	>100 mV to 5.5 V	

1 System Description

This TI Design is inspired by the need to monitor the health of motors and machines to accurately predict and schedule maintenance (or replacement) while minimizing cost and down time during industrial production. Millions of industrial motors are monitored today with handheld or wired Piezo accelerometer sensing devices. The annual cost of monitoring the these motors is approximately $300 per motor.

Recent advancements in ultralow power processing technologies, radios, and piezo sensor miniaturization have enabled the development and deployment of low-cost, small motor monitors with wireless capabilities. These wireless motor monitors are powered by coin cells that have a battery life of more than 10 years. These systems provide the same broadband sensitivity as existing handheld systems, collect vibrational data, and perform spectral analyses on that data. This integrated intelligence lets you deploy and monitor these systems in difficult-to-reach locations. The money these capabilities save can pay for the systems within a few months.

The wireless motor-monitoring TI Design uses two different, yet electrically equivalent, form factors for development and testing.

These form factors include:

- The modular form factor
- The compact form factor

In the modular form factor, TI LaunchPad™ Development Kits and EM connectors allow you to incorporate multiple of radios and processors with energy-management and sensor subsystems.

The compact form factor uses the MSP430™FR5969 ultra-low power microcontroller unit (MCU) with a CC2650 BLE radio, but can be connected to multiple sensor boards. The standard sensor board supports a PCB® Piezotronic vibration sensor.

The 30-pin expansion connector on the small form factor board enables the base-board to be operated with the MCU, the CC2650 radio, or both. The system software assumes you are using both devices.

NOTE: This TI design focuses on the compact form factor system.

1.1 MSP430FR5969 Ultralow-Power MCU

The MCU is the master controller in the compact form design. The MCU offers a combination of industry-leading power consumption, analog integration, digital integration, and an easy-to-use interface that make it the best choice for monitoring and controlling your machine and motor systems.

The integration of ferroelectric random access memory (FRAM) enables lower-power writes, higher reliability, and higher endurance than in a typical flash-based system. In this design, the MCU manages itself and power-gates the CC2650 radio, the analog sensor subsystem, and voltage regulation. The MCU captures sensor data through SPI, transforms it by Fourier, and stores it to FRAM. The MCU uses the UART to communicate with the radio and iPad or Android device.

1.2 TPL5100 Nano-Power Timer (Sleep Timer)

The TPL5100 nano-power timer is a sleep timer. This timer is configured to wake up the MCU every 16 seconds. This timer can trigger wakeups at longer sleep intervals in real-world applications. The maximum wakeup is 18 minutes. After the sleep timer wakes up the MCU, the MCU gates its own power until completing its tasks. This timer consumes approximately 30 nA of current.

1.3 BQ25570 Ultralow-Power Harvester and Battery PMIC

The BQ25570 device is an ultralow-power harvester and battery PMIC that is operated and recharged by an lithium-ion coin cell battery. The device can harvest energy from any source 100 mV or greater. During a wake-up cycle, the MCU activates the integrated voltage regulator of the harvester and battery PMIC. The harvester and battery PMIC also incorporates a buck converter. You can set this converter to regulate the system voltage from a rechargeable coin cell battery (LIR2032) or a nonrechargable coin cell battery (CR2032).

1.4 CC2650 Ultralow-Power BLE/ZigBee™/6LowPAN SoC (Radio)

The radio is power-gated by the MCU. The MCU can wake up the radio can send a heartbeat advertisement, establish a BLE connection, or establish a ZigBee/6LowPAN connection. This radio communicates with the MCU through UART and can connect to any compatible iOS or Android device through *Bluetooth* Low Energy (BLE). Through the MCU and serial flash, a 6LowPAN or any 802.15.4-based stack can side-load or OTA-update the radio. This update enables the radio to communicate within an 802.15.4 network or with a mobile device.

2 Block Diagram

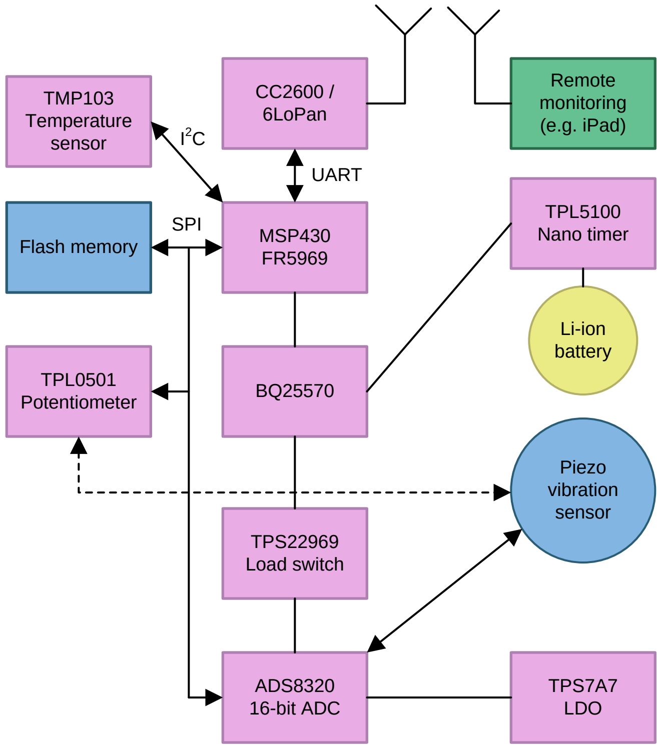

Figure 1. System Block Diagram

3 Highlighted Products

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

3.1 *MSP430FR5969 Ultralow-Power FRAM Microcontroller (MCU)*

The MCU offers unprecedented low-power performance with four ultralow-power consumption sleep modes. The device also has a 16-MHz clock and nonvolatile high-speed FRAM with write and read speeds up to 8 MHz. The device operates at 100 µA/MHz while active and 450 nA in RTC mode. The microcontroller has up to 60 GPIO, supports UART, SPI, and I2C, and operates at a range of 1.8 V to 3.6 V with 256-bit AES encryption.

- Features 100 µA/MHz active current and a 450 nA standby current with RTC.
- Features FRAM that enables quicker and lower-power writes.
- Offers AES encryption to protect information.
- Offers IP encapsulation to minimize cycles.
- Provides ultralow-power system management with the MSP430FR5969 FRAM microcontroller.

3.2 *BQ25570 Ultralow-Power Harvester and Battery PMIC*

This ultralow-power harvester and battery PMIC offers battery charging, battery protection, an internally-set undervoltage level, adjustable overvoltage levels, and a battery good flag pin. The harvester also has a very efficient DC/DC boost charger, cold start voltage ≥ 330 mV (boost charger), and continuous energy harvesting as low as 100 mV. While in sleep mode, the device consumes less than 5 nA and features maximum power point tracking.

3.3 *CC2650 Ultralow-Power BLE/6LowPAN SoC (Radio)*

This ultralow-power BLE radio leads the market with low-power performance for BLE devices. The radio features 6.5-mA power consumption while transmitting and/or receiving RX/TX. This radio also contains a separate ARM M0 core with dedicated ROM and SRAM for the radio stack. This radio also has dedicated LDO and DC-DCs, a 48-MHz ARM M3 core with 128KB of RAM for developing specific application stacks.

- RF Subsystem
  - Features a 2.4-GHz RF transceiver compatible with *Bluetooth* 4.1 Low Energy, IEEE 802.15.4, and proprietary communication protocols.
  - Features programmable MSK, FSK, GFSK, O-QPSK, and CPM modulation nodes.
  - Supports data rates between 50 Kbps and 5 Mbps.
  - Features excellent receiver sensitivity (–97 dBm for BLE and –100 dBm for 802.15.4), selectivity, and blocking performance.
  - Features programmable output power of up to 5 dBm.
  - Features a single-ended or differential RF interface.
  - Features a RF frequency range of 2360 to 2500 MHz.
  - Is best for systems targeting compliance with worldwide radio frequency regulations:
    - ETSI EN 300 328 (Europe)
    - EN 300 440 Class 2 (Europe)
    - FCC CFR47 Part 15 (US)
    - ARIB STD-T66 (Japan)
- Power Management
  - Features wide supply voltage range (1.65 V to 1.95 V or 1.8 V to 3.8 V).
  - Features efficient on-chip DC-DC converter for reduced power consumption.
  - Supports high-granularity clock gating and power gating of device parts.
  - Features flexible frequency of operation.
  - Features flexible low-power modes allowing low-energy consumption in duty-cycled applications.

4 System Design Theory

The wireless motor monitor uses the sleep timer with the MCU to enable ultralow-power duty cycling of a high-precision Piezoelectric vibration sensor. The timer can wake up the MCU from a range of every 16 seconds to 18 minutes and increments a divide-down counter to powerup the sensing and communication subsystems. The MCU periodically captures a 4096 sample FFT. This capture may be compared with previous FFT captures to determine whether to log data or communicate through a *Bluetooth* Low-Energy (BLE) connection.

The radio can communicate with an BLE device (for example an Android device or iPad™) or with a 6LowPAN/ZigBee network (the MCU from the onboard 256 M flash may store and load the 6LowPAN/ZigBee stack). The MCU power gates through separate load switches to the sensor and radio subsystems.

The system may be powered by a lithium-ion or non-rechargeable coin-cell battery and supports solar, thermal, and vibrational energy harvesters.

4.1 Timer Duty Cycling

You can configure the nano timer to wake up the MCU at any interval between 16 seconds to 18 minutes. The nano timer turns on the MCU through a gate and diodes. When the MCU is activated, it can either turn on the voltage regulator, leave it off, or increment the counter. If you configure the MCU to acquire data on a wake cycle, it will turn on the voltage regulator and use the load switch to power the sensor subsystem.

4.2 CC2650 Bluetooth Low Energy (BLE) SoC (Radio)

When a heartbeat advertisement or communication with an iOS or Android device is necessary, the MCU turns on the radio. By default, the software wakes up the radio after 16 seconds of sleep. In the default configuration, the MCU will keep the BLE radio on until it connects with an iOS or Android device to send data. The MCU and the radio communicate through UART. The radio communicates with Android or iOS devices through notifications of 20-byte characteristic updates. To turn off the system, the Android or iOS device must send a command to it.

4.3 MSP430 MCU Power Management and FRAM Logging

Upon wake-up and with diode voltage drops, the battery powers the MCU directly to minimize the time to settle the voltage regulator. If you configure the MCU to acquire data on that wake cycle, it will turn on the voltage regulator and the sensor subsystem to capture vibration data and log it to the FRAM.

5 Getting Started

5.1 Hardware

During the power-up sequence, the timer delivers an active high 30-ms pulse that provides dropped-down power from the battery rail to power up the MCU. The timer delivers these pulses every 16 seconds to 18 minutes depending on the configuration of three resistors. The number of times the MCU must perform a spectral analysis per day dictates the number of times the following statement must be true:

The correct interval of nano-timer wake cycles has passed to perform spectral analysis (for example, 27 eighteen minute wake cycles for spectral analysis every eight hours).

- If false, increment the FRAM variable counter.
- If true, the MCU needs to wake up the harvester to regulate the system power.

For the harvester to come out of its low-power sleep, an active low signal must be supplied from the MCU line (#define BQ_ENABLE). The transition of the harvester from ship mode to active mode takes 100 ms. To prevent the system from powering down after the 30-ms pulse width from the timer, the MCU firmware sends a sets the pin high on the relevant rail (#define BAT_RAIL_ON) that lets the system stay awake after the intitial 30 ms.

NOTE: The system will conserve maximum power when using the BQ25570 buck converter. TI recommends to allow this only for the additional 70 ms that the harvester needs to power on and provide a regulated 3 V (for 16-bit sampling) or 1.8 V (required for 12-bit sampling) output.

When it has turned on the BQ25570 buck converter, the MCU waits 100 ms before disabling the diode regulated battery power to the system. For an image of the wireless monitor main board, see Figure 2

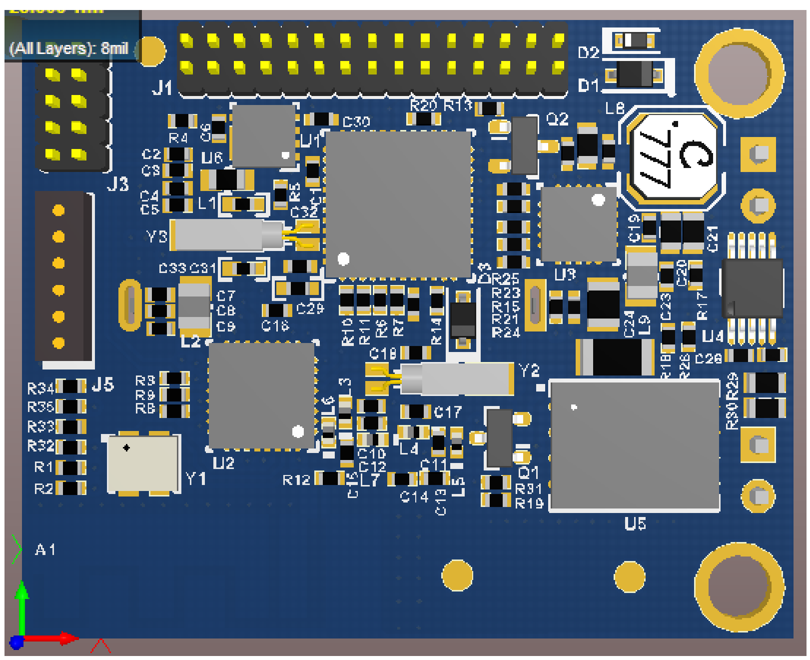

Figure 2. Wireless Monitor Main Board

5.1.1 Analog Front End

To monitor machine vibrations, this design uses a Piezo vibration sensor. Because Piezo sensors have high-impedance output nodes, TI carefully designed the analog front-end (AFE) circuitry to reduce the noise and increase the sensitivity of the system. For the AFE circuitry with Piezo sensor, see Figure 3. 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 capacitor C_1. For this capacitor, see Figure 3. In this model, we disregarded the noise of the sensor because it is typically much less than the noise of the interface circuitry.

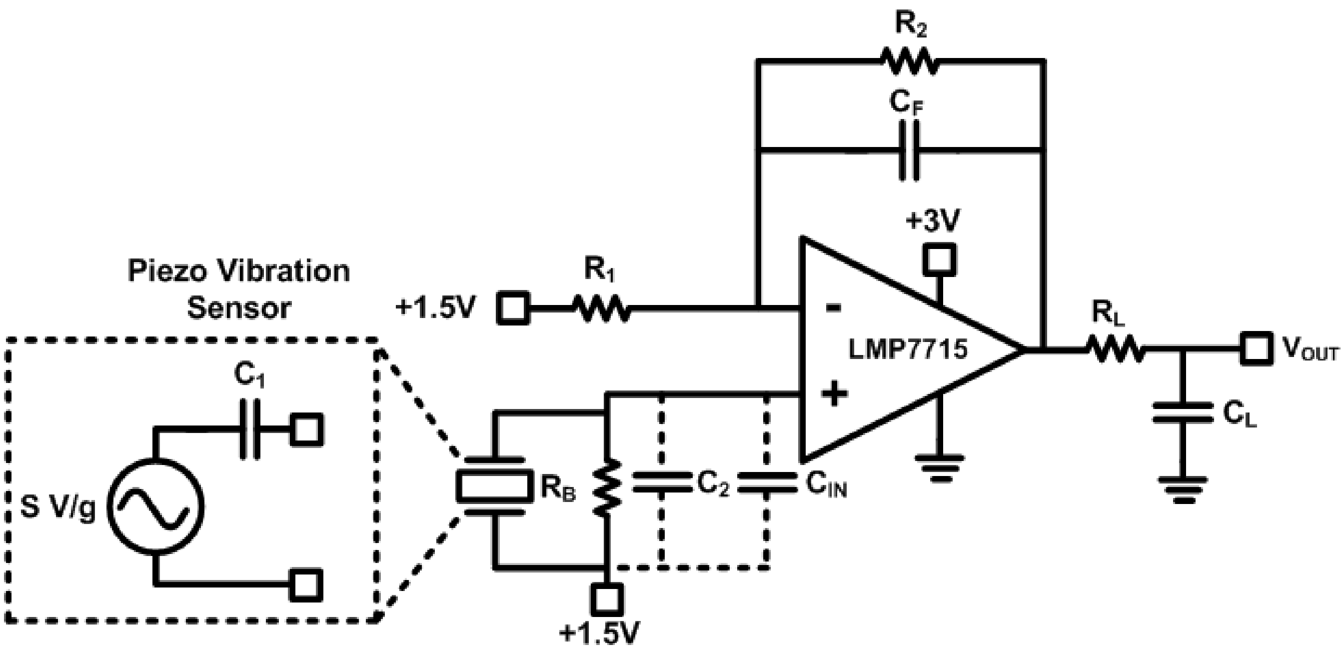

Figure 3. Analog Front-End Schematic With the Piezo Vibration Sensor

The sensitivity at the sensor output, S_S, is defined by the following:

$$S_s = \frac{SC_1}{C_1 + C_2 + C_{IN}} \quad [V/g] \tag{1}$$

S is the sensitivity of the sensor, C_{IN} is the input common-mode capacitor of the amplifier, and C_2 is the parasitic capacitance of the PCB and trace. Because a large C_{IN} reduces the S_S, C_{IN} should be less than C_1. Because the piezo sensors are high-impedance output sensors, CMOS or JFET input amplifiers are preferable but typically have large C_{IN} for low flicker noise. The LMP7715 and the PCB Piezotronics sensor perform well considering these constraints because C_{IN} of the LMP7715 is 15 pF, which is less than the 350-pF capacitance of the PCB Piezotronics sensor. The LMP7715 has low-input referred voltage noise, V_n, and low-input referred current noise, The LMP7715 can be operated with the low-supply voltage at 3 V.

The sensitivity at the amplifier output, S_{AMP}, is defined by the following:

$$S_{AMP} = \frac{SC_1}{C_1 + C_2 + C_{IN}} \times \left(1 + \frac{R_2}{R_1}\right) \quad [V/g].$$

because the amplifier gain is $1 + \frac{R_2}{R_1}$

The resistor (R_B), is necessary to bias at the input and sets a high-pass filter with the sensor output capacitance (C_1).

The cut-off frequency of high pass filter is approximately $\frac{1}{2\pi R_B (C_1 + C_{IN})}$ [Hz] (2)

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

The cut-off frequency of low pass filter 1 is $\frac{1}{2\pi R_L C_L}$ [Hz]

The cut-off frequency of low pass filter 2 is $\frac{1}{2\pi R_2 C_F}$ [Hz]

The noise at the amplifier input can be calculated by:

$$\sqrt{4kT \times R_1 // R_2 + {V_n}^2 + {I_n}^2 \times (R_1 // R_2)^2 + [{I_n}^2 + \frac{4kT}{R_B}] \times [\frac{1}{2\pi f (C_1 + C_{IN})}]^2} \quad [V/rtHz] \tag{3}$$

assuming $C_2 << C_{IN}, R_B >> \frac{1}{2\pi f (C_1 + C_{IN})}$

the input referred noise of the AFE including the sensor can be calculated by

$$\frac{\text{Noise at the amplifier imput}}{S_S} \tag{4}$$

For design parameter examples, see Table 2.

Table 2. Parameter Examples

PARAMETER	VALUE
C1	350 pF
C2	<5 pF
RB	10 MΩ
R1	100 Ω
R2	10 kΩ
Gain	101 V/V
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/rtHz
Input referred noise of the AFE at 1 kHz	1.4 µg/rtHz

5.1.2 Power Management

TI designed the wireless motor monitor to be powered by either a primary lithium coin cell (CR2032) or a rechargeable lithium coin cell (LIR2032). In the LIR2032 configuration, the BQ25570 device is connected to an energy harvester (solar/thermal/vibration/etc.) through the J6 connector on the form factor design. Two diodes, connected to the battery output, ensure that the charging voltage (4.2 V) does not exceed the maximum operating voltage of the system (3.6 V). In the CR2032 configuration, replace the two diodes with 0-Ω resistors to maximize battery life.

The default configuration of the sleep timer is D0, D1, and D2 set to ground. This configuration provides the fastest wake-up period (16 s). Populating zero Ω resistors for D0, D1, and D2 to VCC will provide the slowest wake-up period (18 minutes). When the timer wakes up the MCU, the software will activate the analog subsystem, acquire data, compute the data, store the data a 4-K FFT to FRAM, turn on the BLE radio, and then wait for a connection. When a connection is established, the MCU transmits the first 400 points of the FFT and then repeats the process.

The iPad application enables the connection mode by default for MCU wakeups. The MCU will wake up, capture data, capture FFT, store sensor data, turn on the radio, and wait for a connection. You can observe the power consumption of the other modes by setting the operational mode through the iPad. The system will execute the subsequent wake-up cycle in operational mode before returning to connection mode.

5.1.3 Wireless Communication

The wireless radio is configured for a 100 ms advertisement/connection interval. Each advertisement or connection interval consumes approximately 6 mA of RX/TX current for approximately 3 ms with 1-µA sleep current between advertisement or connection intervals. The advertisement or connection interval may be configured to longer periods through software. Each connection interval enables communication of 20 bytes of data.

The radio is connected to the MCU through RX/TX UART on radio D0 and D1 pins. Both of these pins along with the MCU pins are connected to the 30-pin expansion header (J1). The analog sensor board connects these pins to each other (communication between the MCU and radio is only enabled when the sensor board is installed).The radio has two antenna options. An antenna SMA connector may be installed (J2) or the integrated PCB antenna may be used. Selection of the desired antenna is determined by population (or depopulation of a 0-Ω resistor [R12]) The default system configuration uses the PCB antenna.

5.1.4 Packaging

The complete design is packaged in a 3D-printable enclosure that you can magnetically couple to any ferrous surface. The enclosure is hermetically sealed. The STL design files are included with this design. Reducing the mass of the complete system is critical to both enabling easier deployments and minimizing mechanical packaging requirements. Because high-G vibrating environments are likely to compromise the integrity of the packaging and vibrational coupling over time, TI recommends milling the design in aluminum or another metal for industrial deployments.

5.2 Firmware

For a flow chart that illustrates firmware control, see Figure 4.

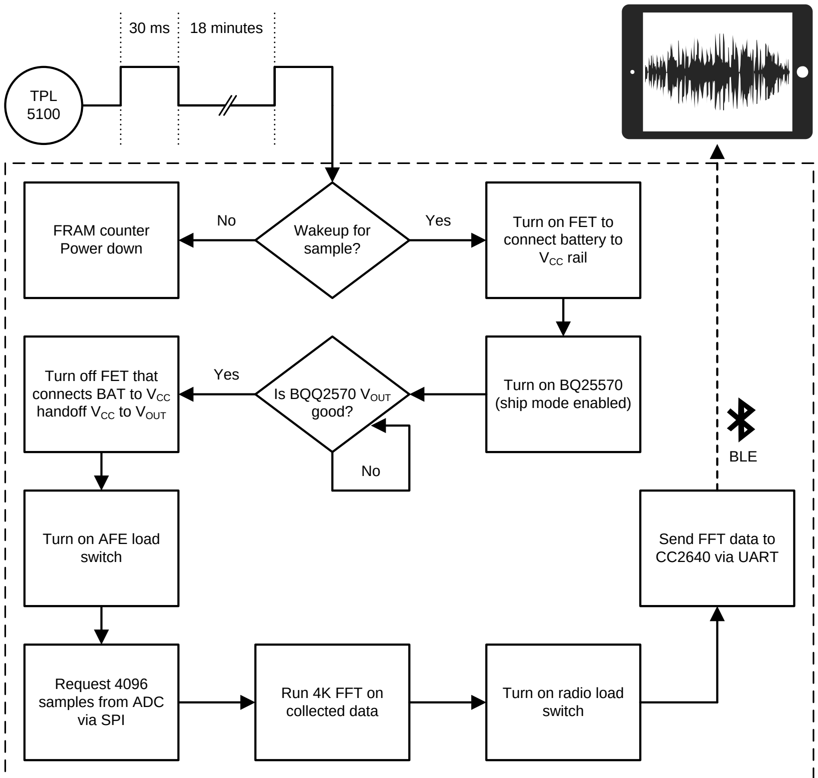

Figure 4. Firmware Control Flow Chart

To use the modular design with a LaunchPad and EM module, leave the MCU and radio unpopulated. The system software may be used with a MSP430FR5969 LaunchPad Development Kit and a CC2650 EM. To use the smaller form factor design, the onboard MCU and radio may be programmed with a MSP430FR5969 LaunchPad and a SmartRF™06 EVM.

The code in Figure 5 was developed and built with Code Composer 6.0.1 using the TI v4.3.5 compiler. To compile the firmware on the MCU, ensure you make the following modification to the linker file (lnk_msp430fr59691.cmd):

```
GROUP(SIGNATURE_SHAREDMEMORY)
{
   .ipesignature   : {}              /* IPE Signature                    */
   .jtagpassword   : {}              /* JTAG Password                    */
} > IPESIGNATURE

.bss          : {} > RAM             /* Global & static vars             */
.data         : {} > RAM             /* Global & static vars             */
.TI.noinit    : {} > FRAM             /* For #pragma noinit               */
.stack        : {} > RAM (HIGH)      /* Software system stack            */

.infoA       : {} > INFOA          /* MSP430 INFO FRAM  Memory segments */
.infoB       : {} > INFOB
.infoC       : {} > INFOC
.infoD       : {} > INFOD
```

The change is: .TI.noinit : {} > FRAM /*For #pragma noinit*/

Figure 5. FRAM Initialization

Initializing this NOINIT pragma to nonvolatile FRAM, instead of RAM, keeps certain variables unchanged between power cycles.

In the design folder, the DSP library is in the zip file, WMM.zip.This zip file should compile.

The *flash_Driver_FR5969.c* and *flash_driver.h* file are also included in the build. This code includes the function set to read and write to the flash memory module. TI has developed the module for the MCU.

5.2.1 Building and Loading the CC2650 Firmware

The CC2650 application stack was developed and tested with the IAR SDK. Code Composer Studio should also be able to compile and flash the code. This scenario has not been tested.

5.2.2 Loading and Running the iPad App

To use the iPad application for this design, download and install the TechBASIC app from the iTunes app store™. The code was written and tested in TechBASIC, which lets you collect data wirelessly from the radio and then graph the FFT.

5.2.3 ADS8320 – 160-Bit ADC

The ADS8320 ADC device (ADC) connects to the Piezo shock sensor signal chain and powers off by default even after BQ25570 regulation is active. To power on the ADC, the firmware asserts the corresponding GPIO output, *LOAD_SWITCH_A_ON*, from the MCU. When the MCU powers on the ADC, it is ready to use.

After every SPI RX/TX is sent from the MCU to the ADC, data samples are obtained. ISR handles this communication. The int32_t read_ADC (Void) function handles the collection and processing of the data. The function also formats and returns the sample as adc_output. On the MCU, the timer (TAO) ISR sets the sample rate set to 10 kHz by default. The system performs a 4-K FFT. At this rate, 4096 samples will be collected at 10 kHz and stored in FRAM.

5.2.4 Flash Memory

The driver can delete the flash memory chip (erase_flash()) entirely or partially based on sectors (erase_sector (char addrs_23_16, char addrs_15_8, char addrs_7_0)) that need the initial memory address of the sector.

Memory writes and reads are performed by these driver functions respectively:

- write_flash()
- read_some_data()

NOTE: The system code provided does not utilize the flash memory. The drivers have been provided and tested for use with specific applications.

5.2.5 DSPLib

This design uses the 4-K real FFT as its DSP function.

6 Test Setup

To test whether the system is working properly, do the following:

1. Obtain a speaker or shaker with a signal generator.
2. Set it to a known frequency.
3. Magnetically couple or bolt the platform to the speaker or shaker.
4. Use the STL file to 3D print the enclosure.
5. Tape or glue a magnet into the enclosure before inserting the electronics.
6. Launch the application on your iOS or Android device.
7. View the graph of the first 400 points of the 4-K FFT.

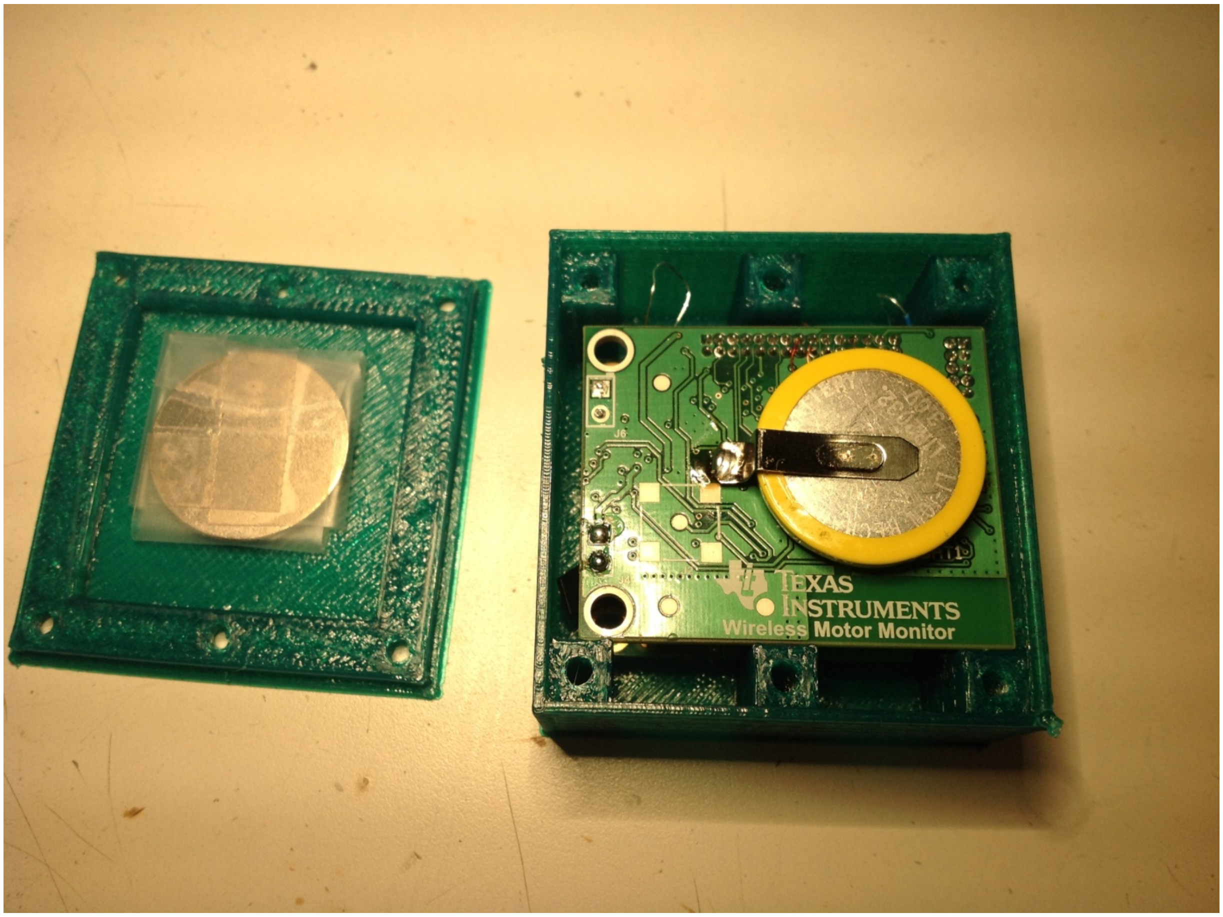

Figure 6. Wireless Motor Monitor in 3-D Printed Enclosure with Magnet

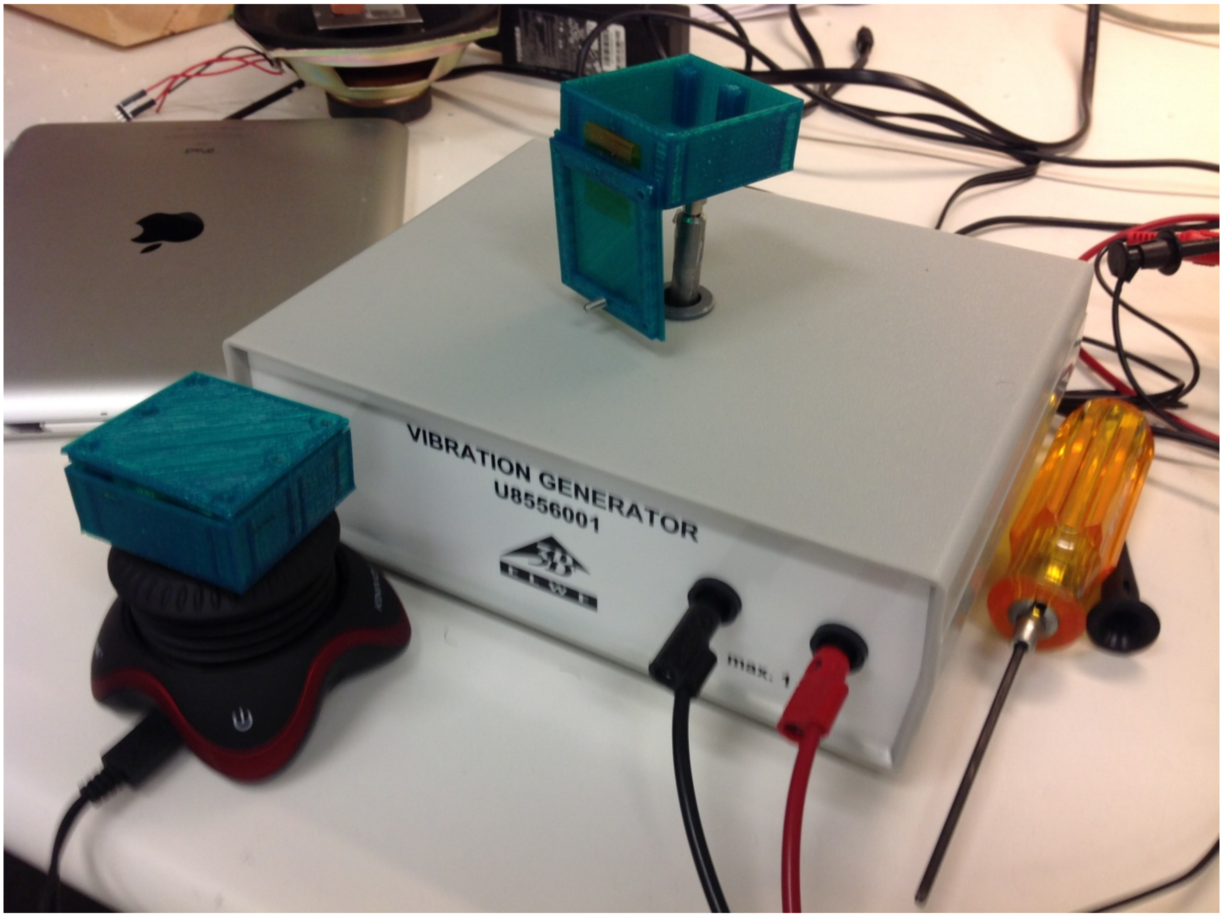

Figure 7. Portable Speaker/Vibration Generator for Uncalibrated Functional Testing

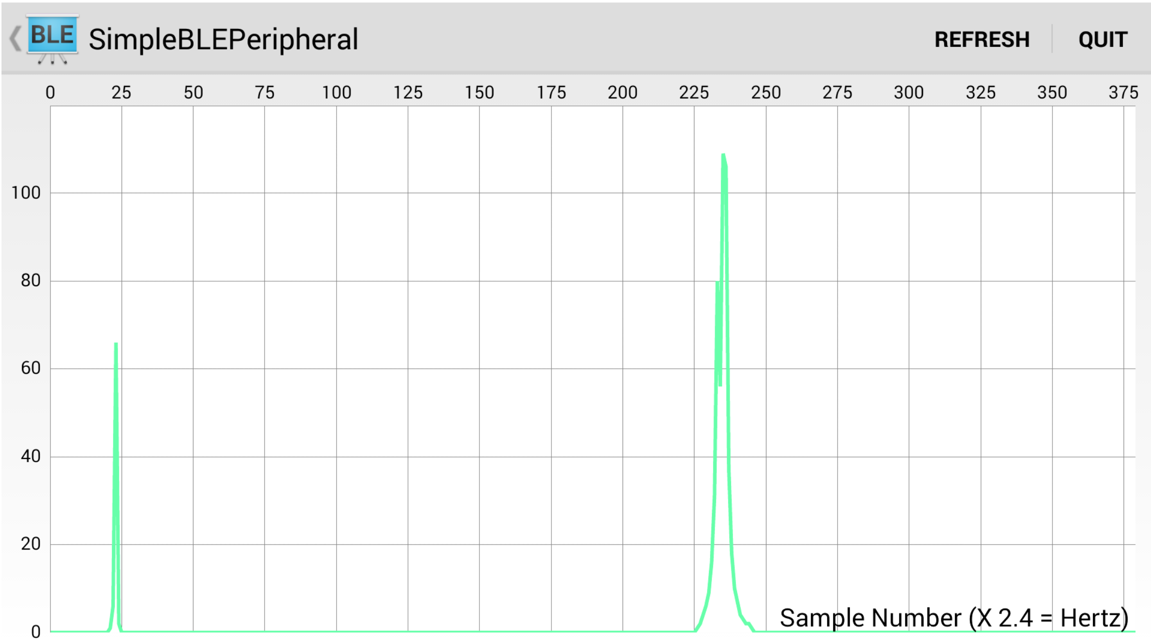

Figure 8. Android Screen Shot of FFT at 600-Hz Excitation With Portable Speaker

7 Test Data

7.1 Testing of Vibration Sensor

The speaker and signal generator application are a low cost and easy-to-use method for verifying whether a system is working. The speaker may produce vibrations at a given frequency with any tone producing application. For an example of this, see Figure 9. Download this app to your iOS devices from the iTunes app store. With this app, you can produce two white noise tones at varying strengths.

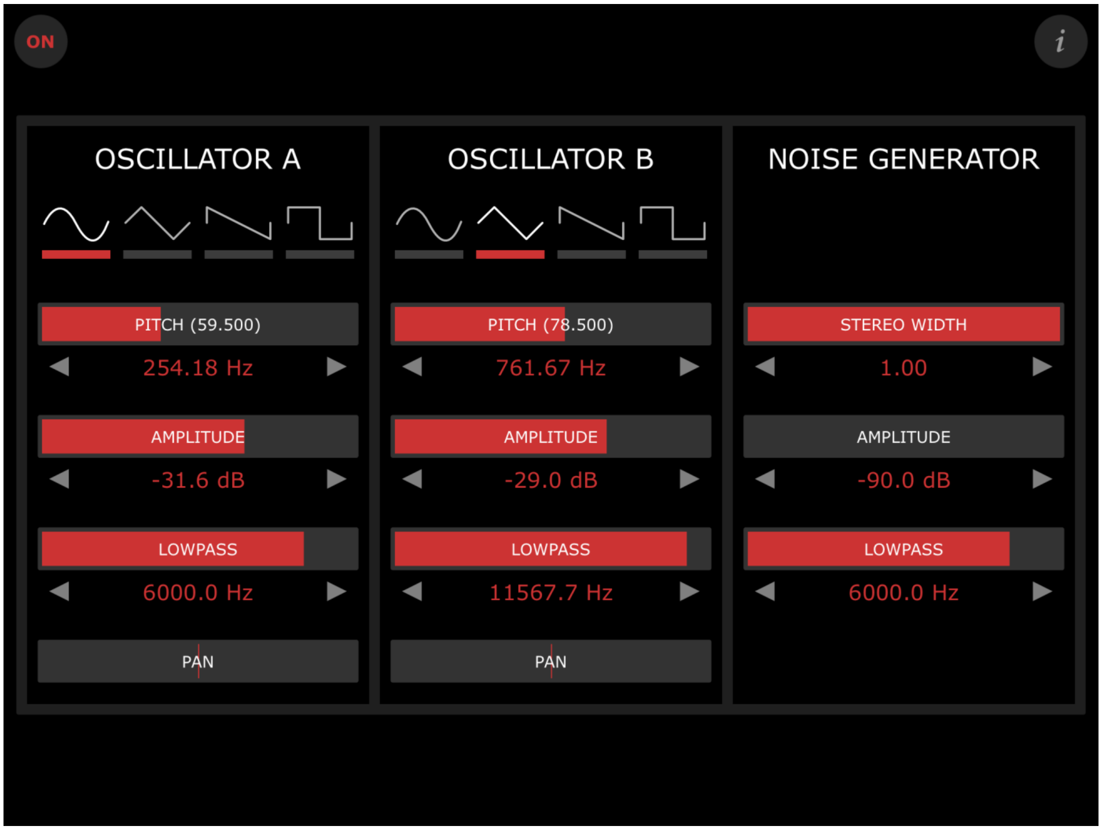

Figure 9. Oscillator Signal Generator Application

The system may also be tested and calibrated with an off-the-shelf vibration generator. For an example of an off-the-shelf generator, see Figure 10.

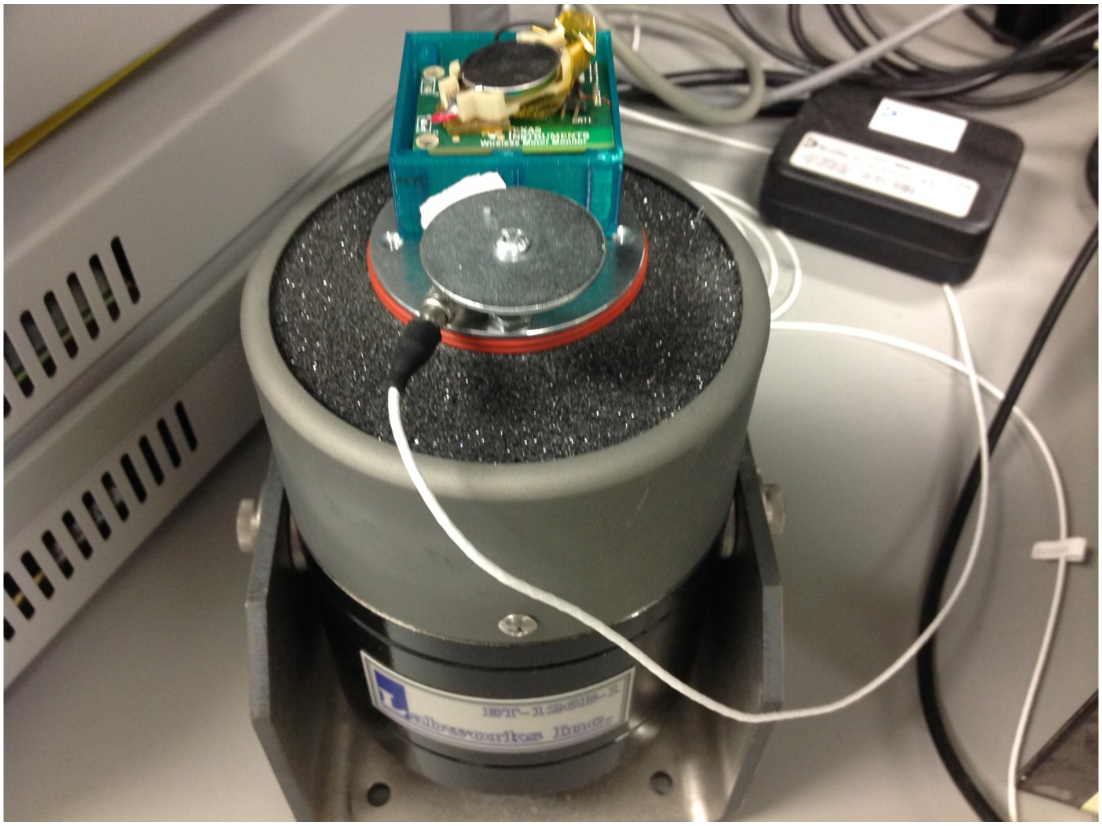

Figure 10. Wireless Motor Monitor on Shaker Calibrated With a Separate Accelerometer

We tested the system with a calibrating accelerometer in Figure 10. We used the ADC and set the AFE gain to 11. We configured the software to output 0.1-g of vibration at 500 KHz, 1.5 KHz, and 2.5 KHz as depicted in Figure 11, Figure 12, Figure 13, Figure 14, and Figure 15.

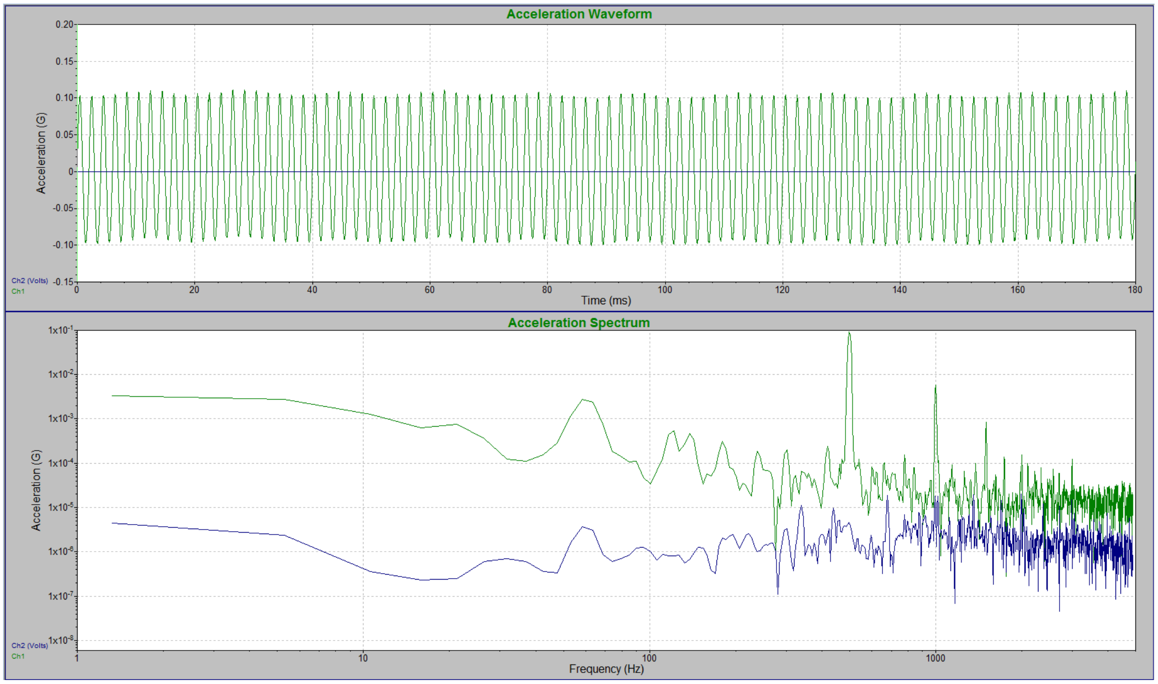

Figure 11. Screen Shot of Vibration View Tool Configured to 500-Hz Excitation at 0.1 g

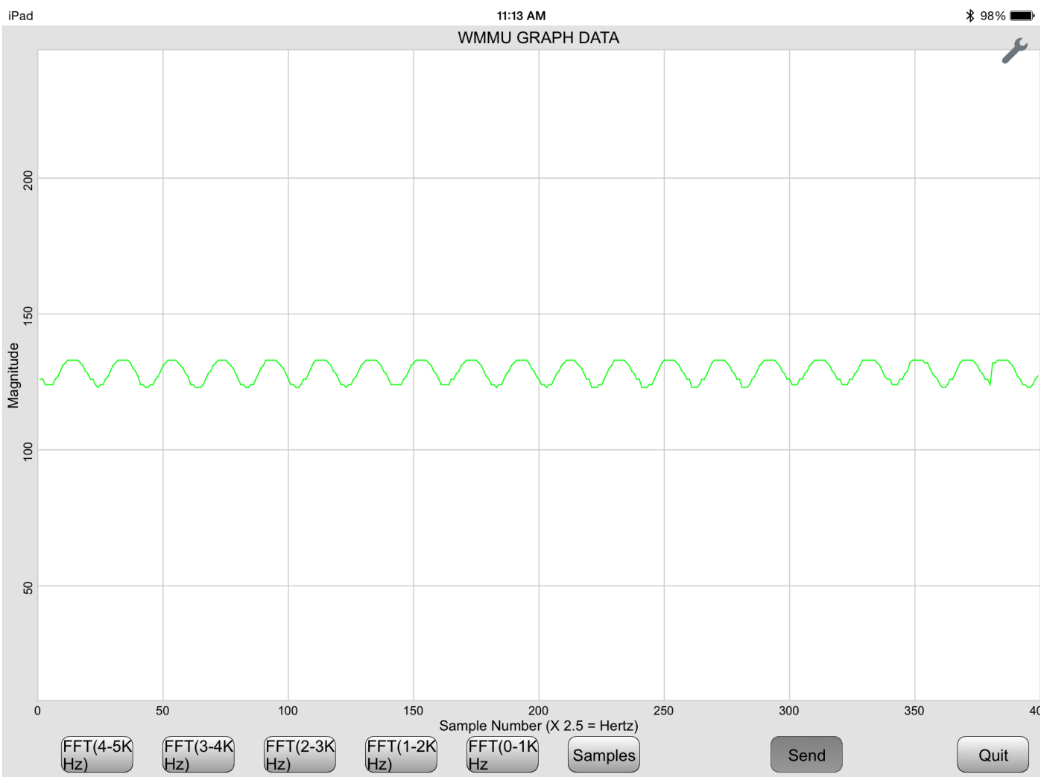

Figure 12. BLE Received Samples at 500-Hz 0.1 g Excitation

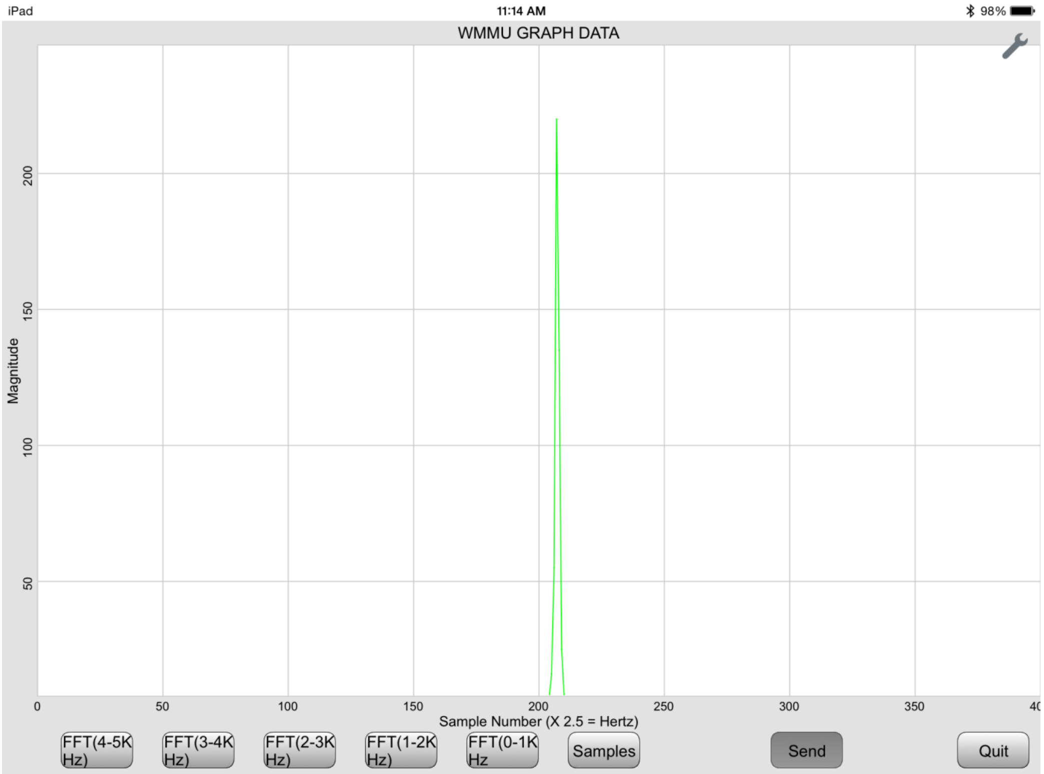

Figure 13. BLE received FFT at 500-Hz 0.1 g Excitation (X 2.4 = Hertz)

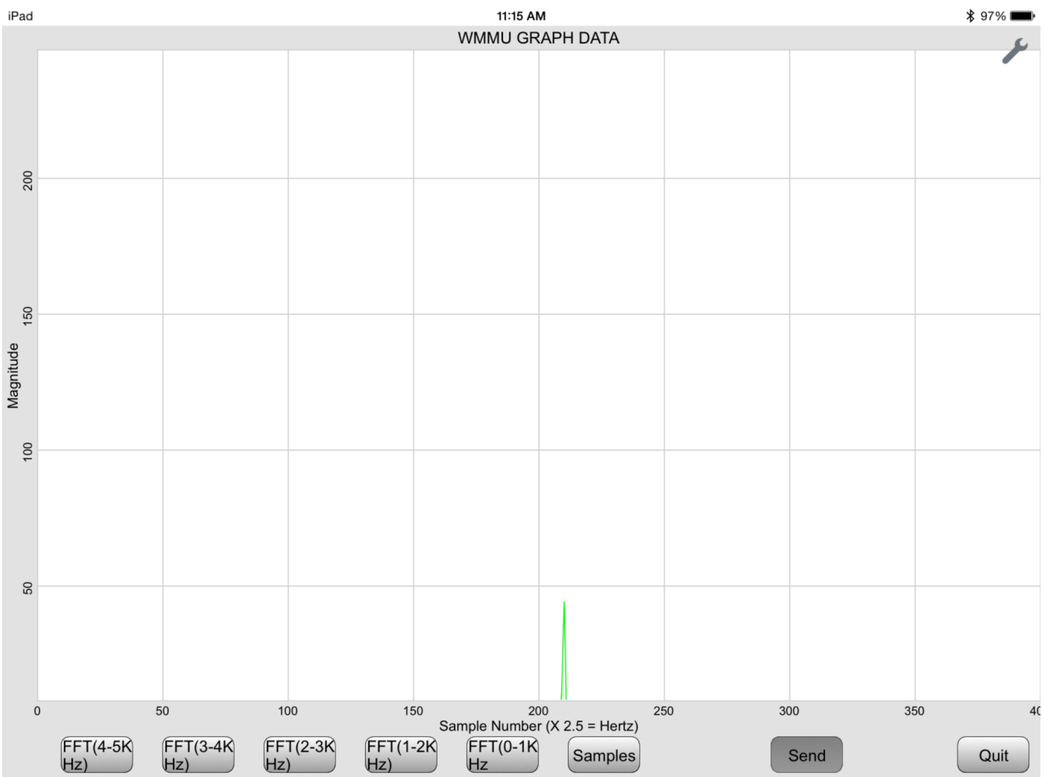

Figure 14. BLE Received FFT at 1.5-kHz 0.1 g Excitation (X 2.4 = Hertz)

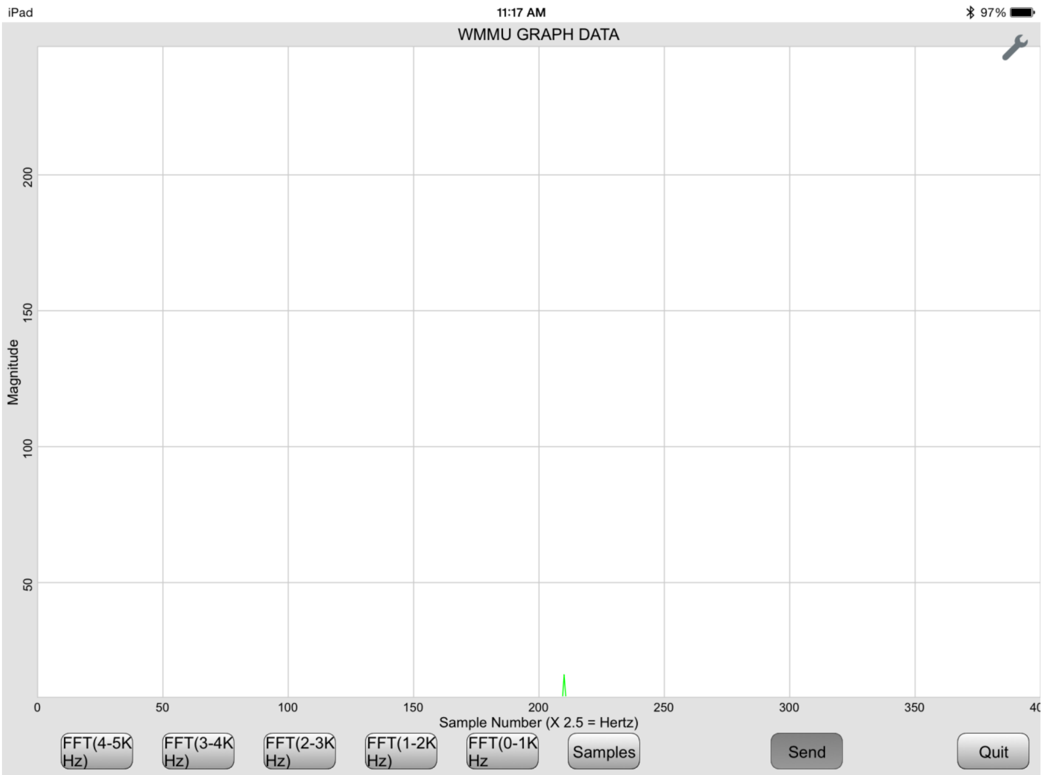

Figure 15. BLE Received FFT at 2.5-kHz 0.1 g Excitation (X 2.4 = Hertz)

7.2 Radio Power Consumption

The radio power consumption was captured as a voltage across a 15-Ω resistor in series with a 3.6-V supply on the SmartRF06 EVM connected to a CC2650 radio. For the power consumption during radio power up, see Figure 16.

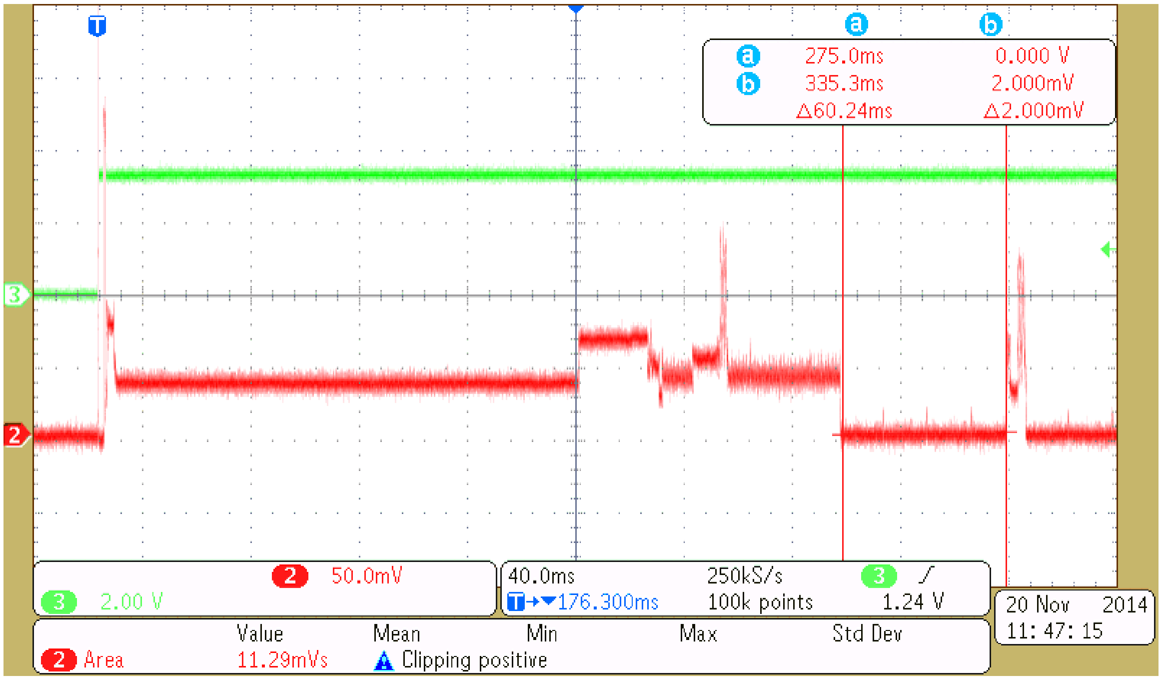

Figure 16. Radio Wakeup Power Consumption

- Power-on start time from VDD: 2.132 ms
- Power-up time: 272.2 ms
- Time to first advertisement after PU finish: 60.24 ms
- PU current consumption: 11.29 mV*s (/15) = 752.67 µA*s 752.67 µA*s 3.6 V × 0.2722 = 737.5564 µJ

For power consumption during an advertisement, see Figure 17.

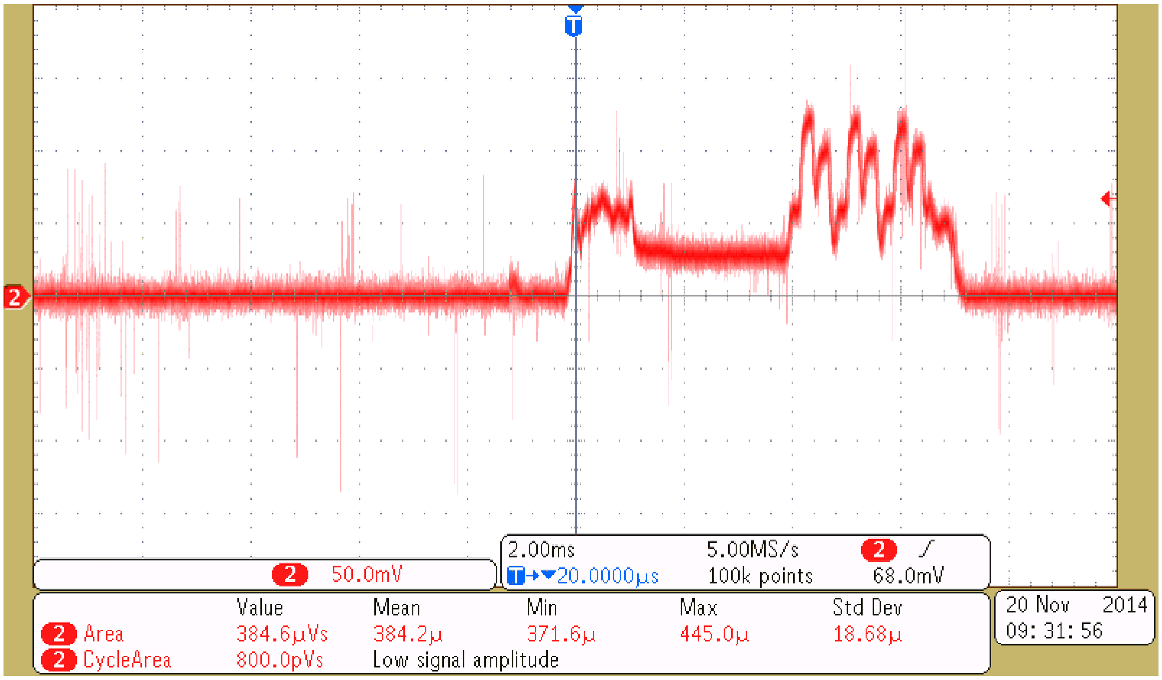

Figure 17. Radio Advertisement Power Consumption

Advertising pulse current consumption:
384.2 µV*s (/15) = 25.613 µA*s » 25.613 µA*s × 3.6 V × 0.00733 = 675.88 nJ

For the power consumption for advertisements every 100 ms, see Figure 18.

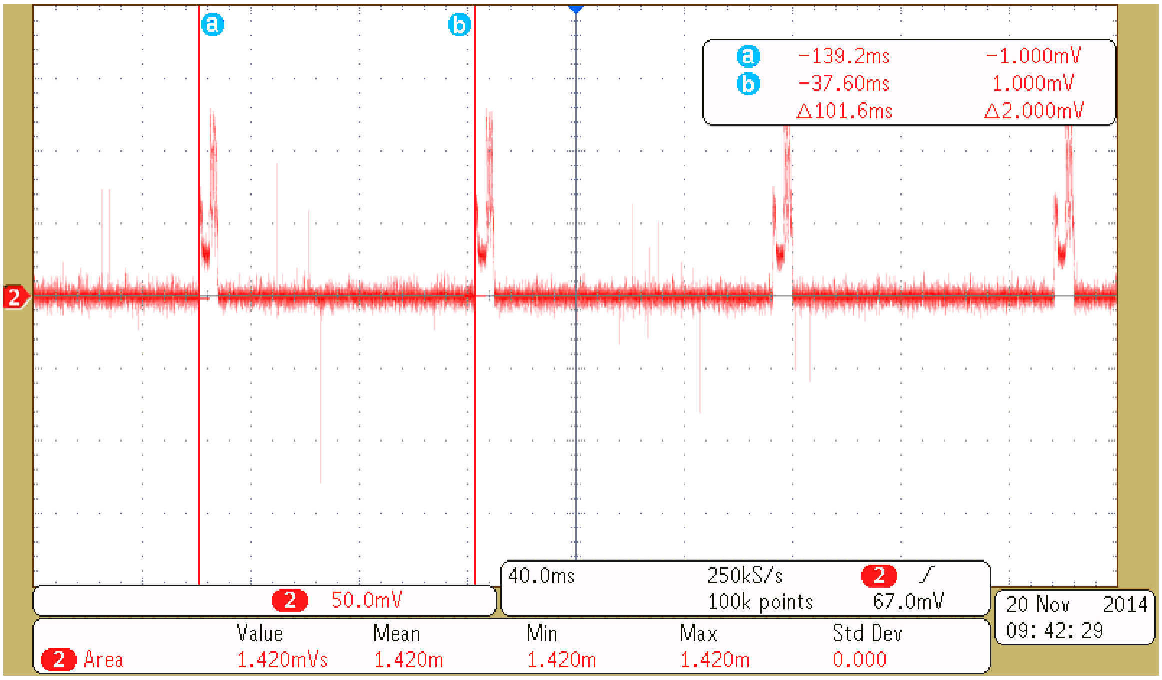

Figure 18. Radio Connection Power Consumption

Rx / Tx pulse width = 13.04ms

Rx / Tx frequency = 200 ms-1 = 5 Hz × Rx / Tx 361.4 µV*s (/15) = 24.0934 µA*s 24.0934 µA*s × 3.6V µ .01304 = 1.131 µJ / Byte (Characteristic)

7.3 Analog Front End

For the analog front end in an active state with a current consumption of approximately 18 mA ,while waiting for the AFE to settle (around 500 ms), and acquiring 4096 data samples at 10 KHz (400 ms) at a battery voltage of 3.8 V, see Figure 19.The current consumed by the AFE proportionally decreases with the voltage applied.

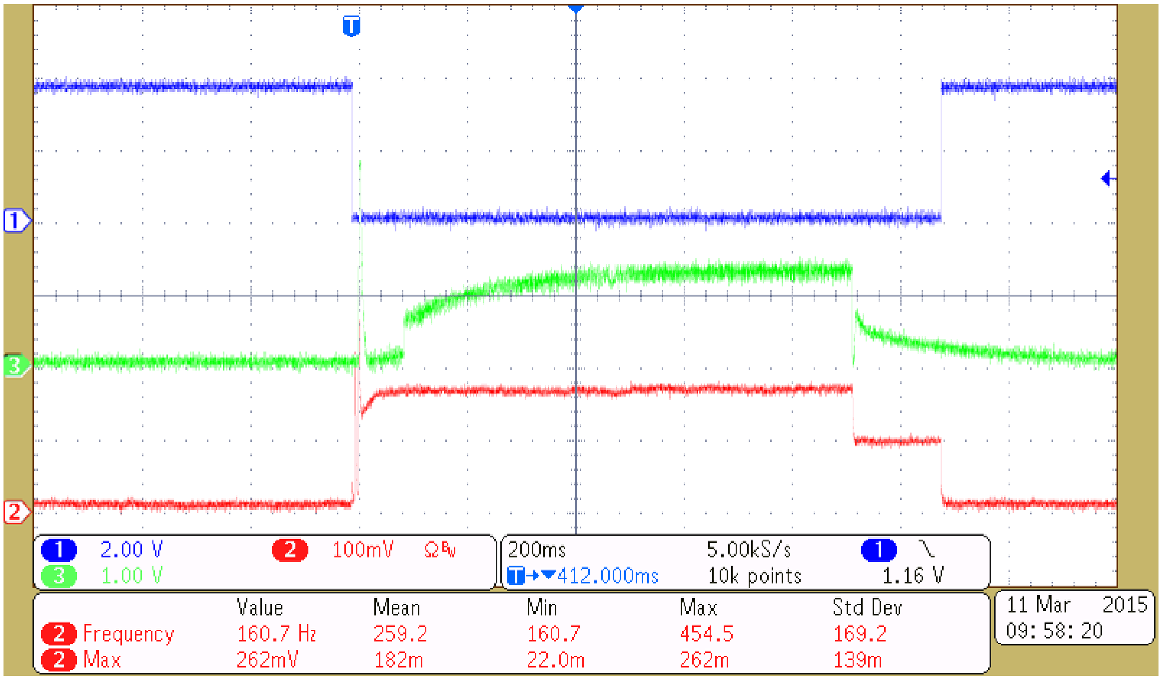

Figure 19. Analog Front-End Power Consumption

After a drop-in current to approximately 10 mA (when the A2D is complete), the system shuts down until the next wake-up cycle. We measured the voltage across a 10-Ω resistor in series with the battery.

7.4 Timer + MCU Power Consumption

For a screen capture measuring the voltage drop across a 10-Ω resistor in series with the battery, see Figure 20.

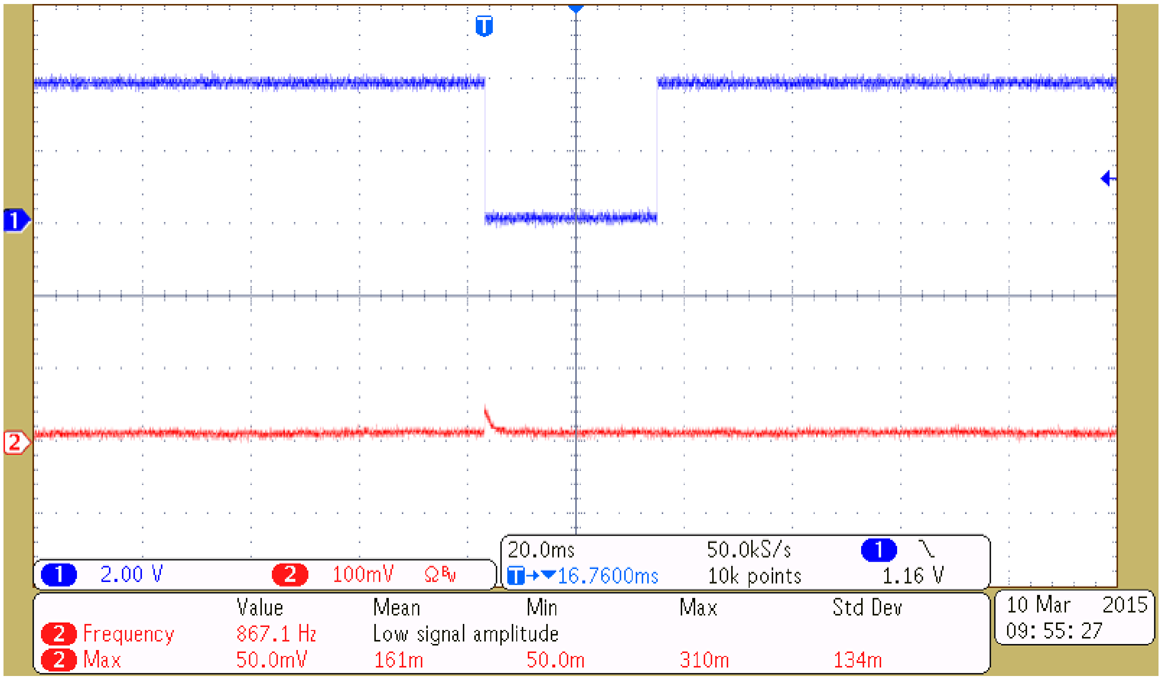

Figure 20. Sleep Timer + MCU Power Consumption

The sleep timer consumes approximately 30 nA until it turns the MCU on. The MCU has a short burst of current (around 5 mA for 2 ms) when first on. Although the voltage to the MCU is kept on for 30 ms by the sleep timer, the MCU goes into power-save mode after incrementing a wake-up timer in FRAM. Assuming a sleep period of around 18 minutes, incrementing the MSP wake timer consumes approximately: 10 uA*s / 18 × 60 = 9 nanoamps*s. The average sleep average current consumption approximately 40 nA.

Considering a case where a motor is monitored three times a day with a radio advertisement:

- Analog current consumption = 18 mA*s / (8 × 3600) = 625 nA (average)
- Radio current consumption = (753 µA*s × .272) + (25.6 uA*s * .013) / (8 × 3600) = 7 nA (average)
- Average total current: 40 + 625 + 7 = 672 nA

Assuming an average of 10% self-discharge per year of the original capacity an LIR2032 on a single charge, a 40 mAh battery has an effective capacity of 24 mAh after 4 years:

24 mAh coin cell battery life = 86.4 A*s / (672 nA) / (3600 × 24 × 365) = more than 4.08 years on a single charge

For the same case, using the integrated 12-bit A2D on the MCU and a CR2032 battery — assuming a 1% per year self-discharge, a 200-mAh battery would have an effective capacity of 154 mAh after 23 years:

154-mAh coin cell battery life = 554 A*s / (672 nA) / (3600 × 24 × 365) = more than 23.8 years

8 Design Files

To download the software files, schematics, bill of materials, PCB layout recommendations, Altium project files, Gerber files, and assembly drawings , see the design files at TIDM-WLMOTORMONITOR.

9 References

- *Op Amp Noise Theory and Applications* (SLOA082)
- *Noise Analysis in Operational Amplifier Circuits* TI Application Report(SLVA043A)

10 About the Author

LEO ESTEVEZ is a researcher at TI, where he develops the next generation wireless sensor and control solutions. Leo recieved an MS (EE) in digital signal processing and a PhD (EE) in Real-Time Vision Systems from Texas A&M in 1993 and 1997, respectively. He also received his pre-med qualifications (biology and bio chemistry) and an MS in Cognitive Neuroscience from the University of Texas at Dallas in 2007 and 2009, respectively.

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