Gas Sensor Platform Reference Design User's Guide

User's Guide

Texas Instruments

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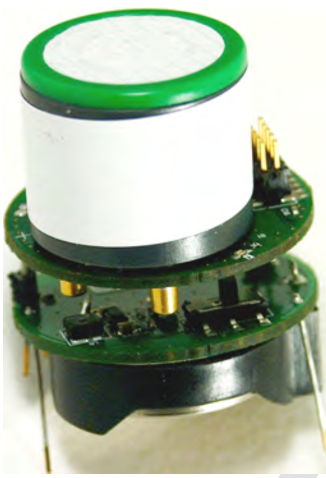
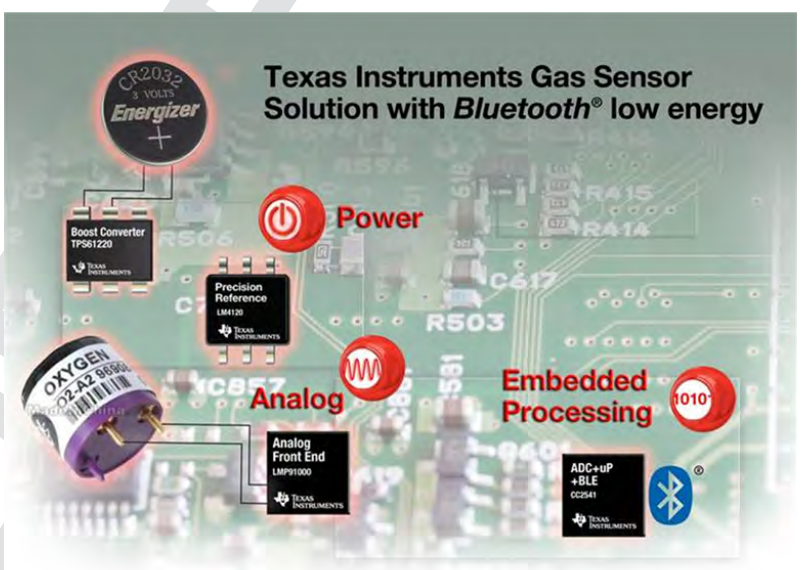
Gas Sensor Platform Reference Design User's Guide

1.1 Introduction

The intent of this user's guide is to describe in detail the Gas Sensor Platform with *Bluetooth* ® Low-Energy Reference Design from Texas Instruments. After reading this user's guide, a user should better understand the features and usage of this reference design platform.





The Gas Sensor Platform with *Bluetooth* low-energy (BLE) is intended as a reference design that customers can use to develop end-products for consumer and industrial applications to monitor gases like carbon monoxide (CO), oxygen (O_2), ammonia, fluorine, chlorine dioxide etc. . BLE adds a wireless feature to the platform that enables seamless connectivity to an iPhone® or an iPad®. Customers can easily replace the targeted gas sensor based on their application, while keeping the same analog front-end (AFE) and BLE design. The system runs on a CR2032 coin-cell battery. AFE from TI — LMP91000 — interfaces directly with the electrochemical cell. The LMP91000 interfaces with CC2541 which is a BLE system on a chip from TI.

An iOS application running on an iPhone 4S® and newer generations or an iPad 3® and newer generations lets customers interface with this reference platform. Customers can use and customize the iOS application, the hardware files and firmware source code of CC2541, which TI provides as an open source. The Gas Sensor Platform with BLE provides customers with a low-power, configurable AFE and the option to integrate wireless features in gas-sensing applications. This platform helps customers access the market faster and helps differentiate from performance, power, and feature sets.

The platform complies with the below certifications on wireless:

- EN 300 328 compliant
- FCC 15.247 compliant
- IC RSS-210 compliant

The platform complies with the below certifications on EMC:

- FCC – FEDERAL COMMUNICATIONS COMMISSION Part 15, Class B
- IC – INDUSTRY CANADA ICES-003 Class B
- EN 301 489-17

The heart of this reference platform is the AFE from TI, the LMP91000. The LMP91000 is perfect for use in micropower, electrochemical-sensing applications. The LMP91000 provides a complete signal-path solution between a sensor and a microcontroller that generates an output voltage proportional to the cell-current. This device provides all of the functionality for detecting changes in gas concentration based on a delta current at the working electrode.

The LMP91000 is programmed to support multiple electrochemical sensors, such as 3-lead toxic gas sensors (see Figure 1-4) and 2-lead galvanic cell sensors (see Figure 1-5) with a single design as opposed to multiple discrete solutions. The AFE supports gas sensitivities over a range of 0.5 to 9500 nA/ppm. It also allows for an easy conversion of current ranges from 5 to 750 µA, full scale.

The adjustable cell-bias and transimpedance amplifier (TIA) gain are programmed through the I^2C™ interface. The I^2C interface can also be used for sensor diagnostics. An integrated temperature sensor can be read by the user through the VOUT pin and used to provide additional signal correction in the µC or monitored to verify temperature conditions at the sensor. The AFE is optimized for micropower applications, and operates over a voltage range of 2.7 to 5.25 V. The total current consumption can be less than 10 µA. Additional power-saving capabilities are possible by switching off the TIA and shorting the reference electrode to the working electrode with an internal switch

The LMP91000 supports many different toxic gases and sensors, and is configured to address the critical parameters of each gas.

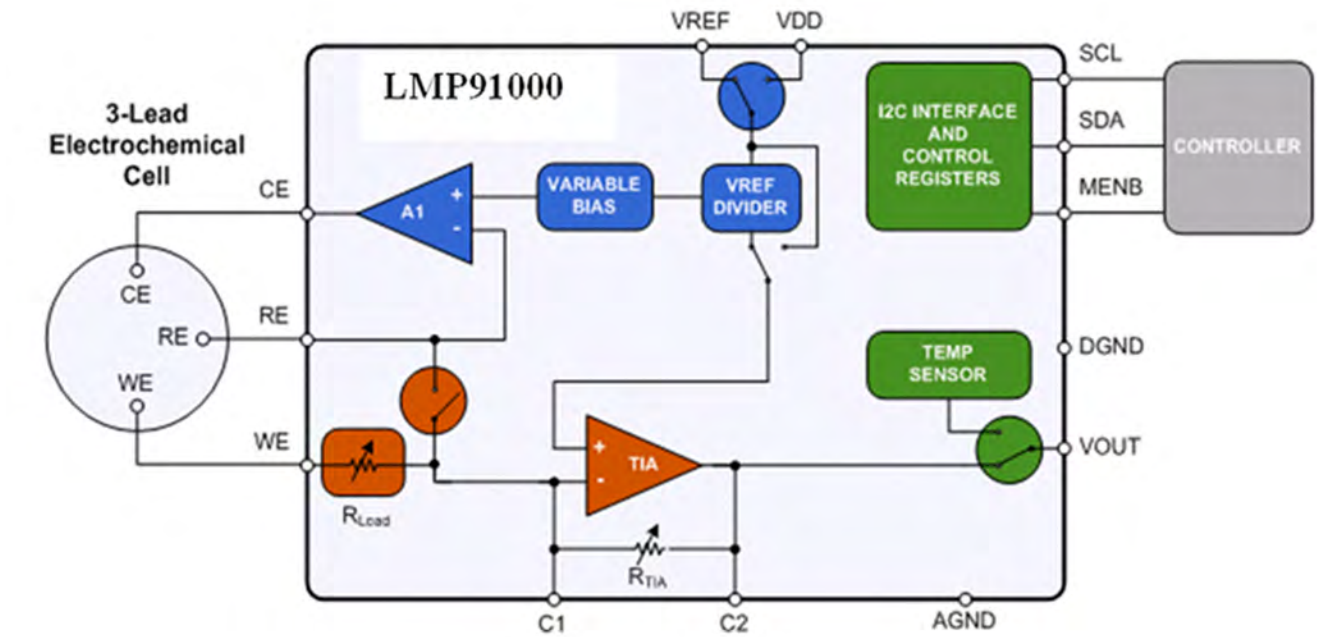


Figure 1-1. Sensor Design

1.1.1 *Fundamental Blocks of LMP91000:*

Transimpedance Amplifier — TIA provides an output voltage that is proportional to the cell current. TIA provides seven programmable internal-gain resistors and allows the external-gain resistor to connect to the LMP91000.

$$(V_{ref\_div} - V_{out}) / (RTIA) = I_{we} \quad (1)$$

$$V_{out} = (V_{ref\_div}) - (RTIA \times I_{we}) \quad (2)$$

Input — The LMP91000 provides a 3-electrode solution — counter electrode (CE), reference electrode (RE), working electrode (WE) (see Figure 1-4), as well as a 2-electrode solution — short the CE and RE (see Figure 1-5).

Variable Bias — Variable bias provides the amount of bias voltage required by a biased gas sensor between RE and WE. This bias voltage can be programmed to be 1% to 24% of the supply, or it can be VREF. The bias can also be negative or positive depending on the type of sensing element.

V_{ref} Divider — This is the voltage at the noninverting pin at TIA. This voltage can be programmed to be either 20%, 50%, or 67% of the supply, or it can be VREF. The V_{ref} Divider provides the best use of the full-scale input range of the analog-to-digital converter (ADC) and sufficient headroom for the counter electrode of the sensor to swing in case of sudden changes in the gas concentration.

- How to select the appropriate V_{ref} divider:
  - If the current at pin WE (I_{we}) is flowing into the TIA, then the V_{ref} divider should be set to 67% of V_{ref}.
  - If I_{we} is flowing out of the TIA, then the V_{ref} divider should be set to 20% of V_{ref}.
    - Assume $V_{ref\_divider}$ is set to 20% of V_{ref}.
    - Assume Variable Bias is set to 2% of V_{ref}.
    - Assume V_{ref} = 4.1V.

    The V_{ref} divider in that case would be 0.82 V. The noninverting input to A1 woul;d be 0.902 V, which is 22% of V_{ref}.

Control Amplifier A1 — A1 is a differential amplifier used to compare the potential between WE and RE. The error signal is amplified and applied to the CE. Changes in the impedance between the WE and RE cause a change in the voltage applied to CE in order to maintain the constant voltage between WE and RE.

Temperature Sensor — An on-board temperature sensor provides a ±3˚C accuracy. The sensor can be used by an external µC to correct for performance over temperature.

Serial Interface — Calibration and programming is done through the I^2C digital interface. Calibration and state-of-health monitoring is enabled by the I^2C interface. As mentioned before, health monitoring is very important because chemical cells can degrade over time.

1.1.2 Examples of Firmware and iOS Calculation

This section explains the signal path and signal processing as implemented in the Gas Sensor Platform, from the sensor to LMP91000, to CC2541 and to the iOS application.

1.1.2.1 O_2 Sensor Example

The following example uses the O_2 sensor from the Alphasense A2 series (see Section 1.3.1).

A change in µA current of the sensor indications a change in gas concentration. The LMP91000 processes the current and uses the linear TIA stage to convert the current to analog voltage (see Figure 1-1). The analog voltage is then sent to CC2541. The CC2541 then converts the raw analog voltage to a digital signal through a 12-bit ADC and transmits the signal through the *Bluetooth* radio to an iOS device. The iOS device then performs postprocessing.

1.1.2.1.1 Postprocessing Steps as Implemented in the iOS

- Covert voltage (binary to decimal).
  - In this example, we assume that CC2541 transmits 0348h in its VOUT field. iOS software converts this hexadecimal voltage into a decimal value:

$$0348h = 840 \quad (3)$$

- Since the ADC is inside the CC2541 is a 12-bit resolution (2s complementary).
  - Thus the ADC resolution inside CC2541:

$$2.5\ V / (2^{11}-1) = 0.001221 \quad (4)$$

  - Note: LM4120 provides a fixed 2.5V precision reference to both LMP91000 and CC2541 in this reference platform and thus we have used 2.5 V above to calculate the ADC resolution inside CC2541 .
- Multiply the decimal value from Equation 8 with the ADC resolution:

$$840 \times 0.001221 = 1.025\ V \quad (5)$$

$(V_{ref\_div} – V_{out}) / (RTIA) = I_{we\_fresh\ air}$

  - V_{ref_div} here is 67% of V_{ref}.
  - RTIA above is set to 7000.
  - Thus current at pin WE (I_{we}) flowing into the TIA is ~91 µA (fresh air calibration). (6)
- To change the O_2 concentration, if you exhale (breathe out) on the O_2 sensor; the VOUT would increase. Let's assume that CC2541 transmits 03B0h in its VOUT field. 03B0h will translate to 944 in decimal. (see Equation 8).
  - 944 × 0.001221 = 1.152 V
    - Thus current at pin WE (I_{we}) flowing into the TIA in this case would be: (1.667– 1.152) / 7000 = 73.5 µA
- In Equation 11, the calibrated fresh air WE (I_{we}) value is 91 µA. For calibration, this can be set to correspond - 20.9%.
- When we exhale (breathe out) on the O_2 sensor; the normalized O_2 percentage would then be:

$$(73.5 \times 20.9) / 91 = 16.88\% \quad (7)$$

1.2 CO Sensor Example

The following example uses the CO sensor from the Alphasense CO-AF series (see Section 1.3.1).

A change in µA current of the sensor indications a change in gas concentration. The LMP91000 processes the current and uses the linear TIA stage to convert the current to analog voltage (see Figure 1-1). The analog voltage is then sent to CC2541. The CC2541 then converts the raw analog voltage to a digital signal through a 12-bit ADC and transmits the signal through the *Bluetooth* radio to an iOS device. The iOS device then performs postprocessing.

1.2.1 Postprocessing Steps as Implemented in the iOS

- Covert voltage (binary to decimal).
  - In this example, we assume that CC2541 transmits 019Fh in its VOUT field. iOS software converts this hexadecimal voltage into a decimal value:

$$019Fh = 415 \tag{8}$$

- Since the ADC is inside the CC2541 is a 12-bit resolution (2s complementary).
  - Thus the ADC resolution inside CC2541:

$$2.5\ V / (2^{11}-1) = 0.001221 \tag{9}$$

  - Note: LM4120 provides a fixed 2.5V precision reference to both LMP91000 and CC2541 in this reference platform and thus we have used 2.5 V above to calculate the ADC resolution inside CC2541 .
- Multiply the decimal value from Equation 8 with the ADC resolution:

$$415 \times 0.001221 = 0.506\ V \tag{10}$$

$$(V_{ref\_div} - V_{out}) / (RTIA) = -\ I_{we\_fresh\ air}$$

  - As I_{we} is flowing out of the TIA in case of CO sensor, then the V_{ref} divider should be set to 20% of V_{ref}.
  - RTIA above is set to 7000.
  - Thus current at pin WE (I_{we}) flowing out of the TIA is ~857nA (fresh air calibration). (11)
- Based on the CO-AF specification, the sensitivity of the sensor is 55-90nA/ppm. In the iOS software, the sensitivity is set to 70nA/ppm (~average of the range).
  - 857nA × 70nA/ppm= ~12ppm
- Note: The RTIA for the CO-AF sensor is set to 7000. This ensures that the full range of the CO-AF sensor (0-5000ppm) can be utilized without clipping.

1.3 Supported Sensor Types

The Gas Sensor Platform from TI can be used either with a 3-lead amperometric cell (not included) (see Figure 1-4) and a 2-lead galvanic cell (not included) in potentiostat configuration (see Figure 1-5) by a minor resistor change shown in Figure 5-4.

- For a 3-lead amperometric cell (CO), R43 must be un-installed.
- For a 2-lead galvanic cell (O_2) R43 must be installed.

Figure 1-2. CO Setup

Figure 1-3. O_2 Setup

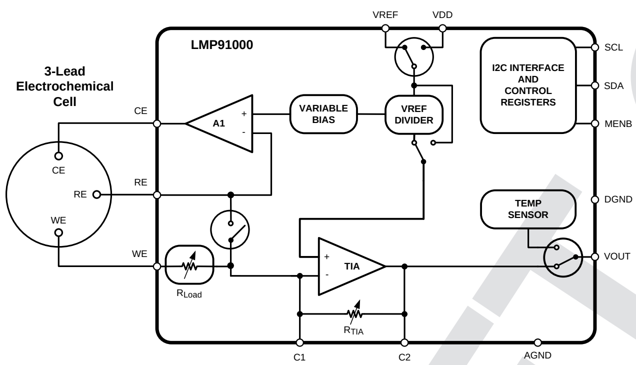


Figure 1-4. 3-Lead Amperometric Cell

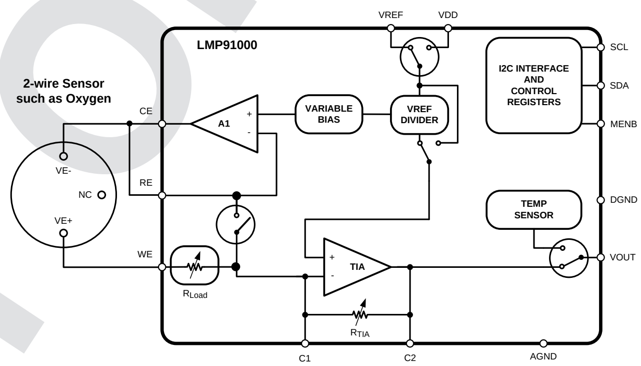


Figure 1-5. 2-Lead Galvanic Cell In Potentiostat Configuration

1.3.1 WEBENCH® Support

TI recommends that customers use WEBENCH for their sensor-type design. Refer to Figure 1-6, Figure 1-7, and the WEBENCH open design tool at http://www.ti.com/product/lmp91000. The WEBENCH tool lists all of the sensor types compatible with LMP91000.

NOTE: The default firmware and the iOS software in the Gas Sensor Platform from TI are designed to support the CO-AF from Alphasense (http://www.alphasense.com/industrial-sensors/alphasense_sensors.html) as well as the O2-A2 from Alphasense. Customers can easily update the firmware and the iOS software to support additional sensor types. For firmware updates see Section 7.2.

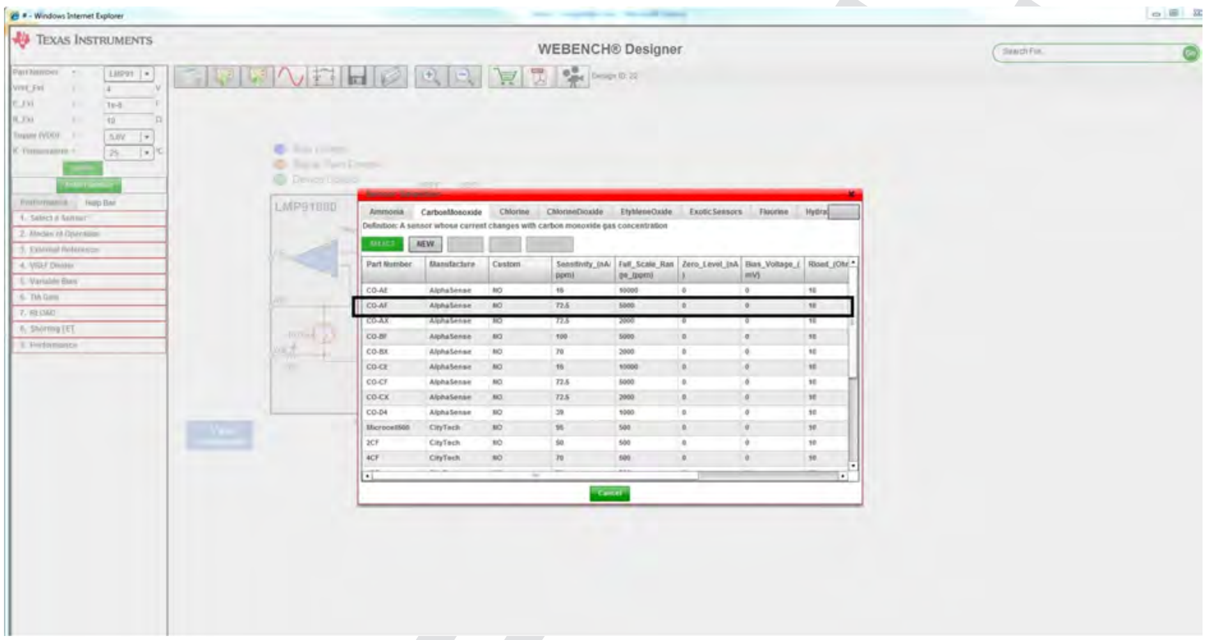


Figure 1-6. WEBENCH CO

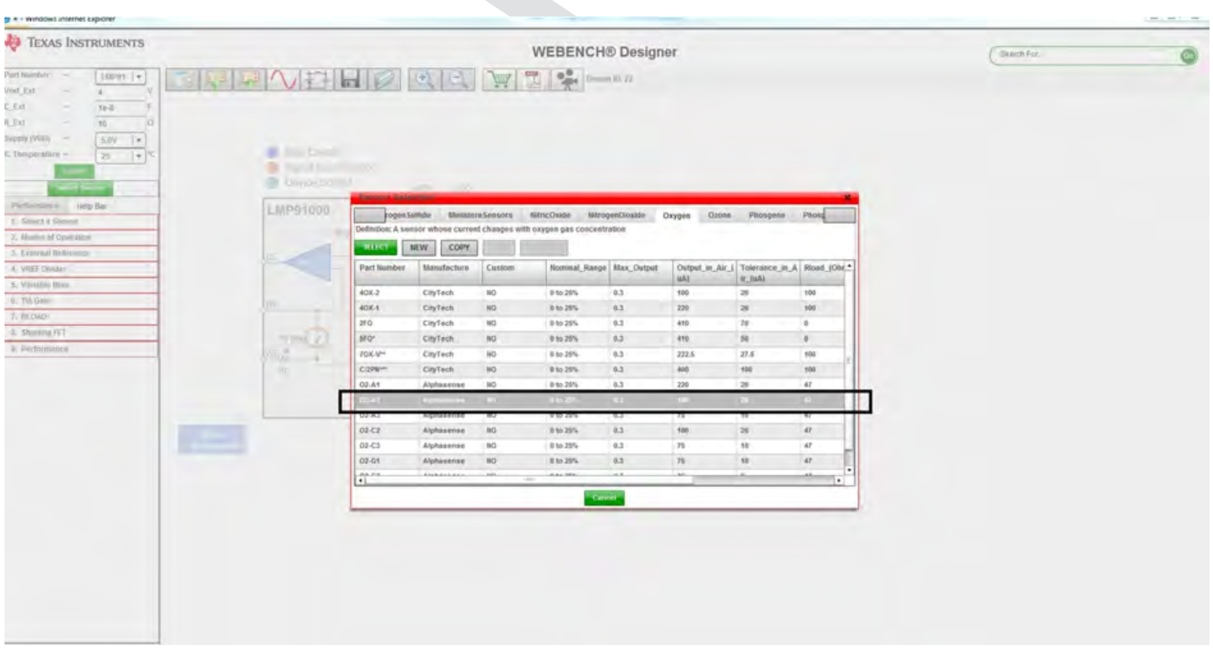


Figure 1-7. WEBENCH O_2

Features

2.1 Gas Sensor Platform With BLE Design Features

- Coin-cell operation (CR2032)
- Low-power configurable AFE (LMP91000) that provides flexibility for customers to use the same AFE for different gas-sensing platforms and configure different platforms with a simple firmware update
- Provides reference design for BLE antenna design - leveraging low-cost trace antenna
- Enables customers to use the platform to incorporate wireless features in gas-sensing applications
- TI provides BLE firmware and iOS application software as open-source to help customers get to the market faster.
- The platform is comprised of two boards that are stacked together and are referred to as SAT0009 (power board) and SAT0010 (AFE and *Bluetooth* board).

LMP91000

- Supply voltage 2.7 to 5.25 V
- Supply current (average over time) <10 µA
- Cell-conditioning current up to 10 mA
- Reference electrode bias-current (85°C) 900 pA (max)
- Output drive-current 750 µA
- Complete potentiostat circuit to interface to most chemical cells
- Programmable cell-bias voltage
- Low-bias voltage drift
- Programmable TIA gain 2.75 to 350 kΩ
- Sink and source capability
- I^2C-compatible digital interface
- Ambient operating temperature –40°C to +85°C
- Package: 14-pin WSON
- Supported by WEBENCH Sensor AFE Designer

LM4120

- Small SOT23-5 package
- Low dropout voltage: 120 mV Typ @ 1 mA
- High output voltage accuracy: 0.2%
- Source and sink current output: ±5 mA
- Supply current: 160 µA Typ.
- Low temperature coefficient: 50 ppm/°C
- Enable pin
- Fixed output voltages: 1.8, 2.048, 2.5, 3.0, 3.3, 4.096 and 5.0 V
- Industrial temperature range: –40°C to +85°C

TPS61220

- Up to 95% efficiency at typical operating conditions
- 5.5-µ quiescent current

- Startup into load at 0.7-V input voltage
- Operating input voltage from 0.7 to 5.5 V
- Pass-through function during shutdown
- Minimum switching current 200 mA
- Output overvoltage, overtemperature, input undervoltage lockout protection
- Adjustable output voltage from 1.8 to 5.5 V
- Fixed output voltage versions
- Small 6-pin SC-70 package

CC2541

- Radio
  - 2.4-GHz low-energy compliant and Proprietary RF System-on-Chip (SoC)
  - Supports 250-kbps, 500-kbps, 1-Mbps, 2-Mbps data rates
  - Excellent link budget, enabling long-range applications without external front-end
  - Programmable output power up to 0 dBm
  - Excellent receiver sensitivity (–94 dBm at 1 Mbps), selectivity and blocking performance
  - Suitable for systems-targeting compliance with worldwide radio frequency regulations
  - ETSI EN 300 328 and EN 300 440 Class 2 (Europe), FCC CFR47 Part 15 (US), and ARIB STD-T66 (Japan)
- Layout
  - Few external components
  - Reference design provided
  - 6-mm × 6-mm QFN-40 package
  - Pin-compatible with CC2540 (when not using USB or I^2C)
- Low power
  - Active-mode RX down to: 17.9 mA
  - Active-mode TX (0 dBm): 18.2 mA
  - Power mode 1 (4-µs Wake-Up): 270 µA
  - Power mode 2 (Sleep Timer On): 1 µA
  - Power mode 3 (External Interrupts): 0.5 µA
  - Wide supply-voltage range (2 V – 3.6 V)
  - TPS62730-compatible low power in active mode
  - RX down to: 14.7 mA (3-V supply)
  - TX (0 dBm): 14.3 mA (3-V supply)
- Peripherals
  - Powerful 5-Channel direct memory access (DMA)
  - General-purpose timers (one, 16-bit; two, 8-bit)
  - IR generation circuitry
  - 32-kHz sleep timer with capture
  - Accurate digital RSSI support
  - Battery monitor and temperature sensor
  - 12-bit ADC with eight channels and configurable resolution
  - AES security coprocessor
  - Two powerful UARTs with support for several serial protocols
  - 23 general-purpose I/O pins
    - (21 × 4 mA, 2 × 20 mA)

  - I²C interface
  - Two I/O pins with LED-driving capabilities
  - Watchdog timer
  - Integrated high-performance comparator
- Development tools
  - CC2541 Evaluation Module Kit (CC2541EMK)
  - CC2541 Mini Development Kit (CC2541DK-MINI)
  - SmartRF™ software
  - IAR Embedded Workbench® available

2.2 Featured Applications

The Gas Sensor Platform with BLE Reference Platform is designed to demonstrate how a configurable AFE can be used with a low-power wireless radio to provide a reference platform that will help customers develop their next-generation gas-sensing solutions for:

- Industrial: gas-sensing application
- Consumer: carbon monoxide-sensing application
- Healthcare facilities: gas-sensing application

2.3 Highlighted Products

The Gas Sensor Platform with Bluetooth Low-Energy Reference Design features the following devices:

- LMP91000: Sensor AFE System: Configurable AFE potentiostat for low-power chemical-sensing applications.
- CC2541: –2.4-GHz *Bluetooth* low-energy and proprietary SoC.
- LM4120: Precision micropower low dropout voltage reference.
- TPS61220: Low input voltage, 0.7-V boost converter with 5.5-μA quiescent current.

For more information on each of these devices, go to the respective product folders at ti.com.

2.4 Block Diagram

Figure 2-1 shows the block diagram for TI's Gas-Sensor Solution with BLE.

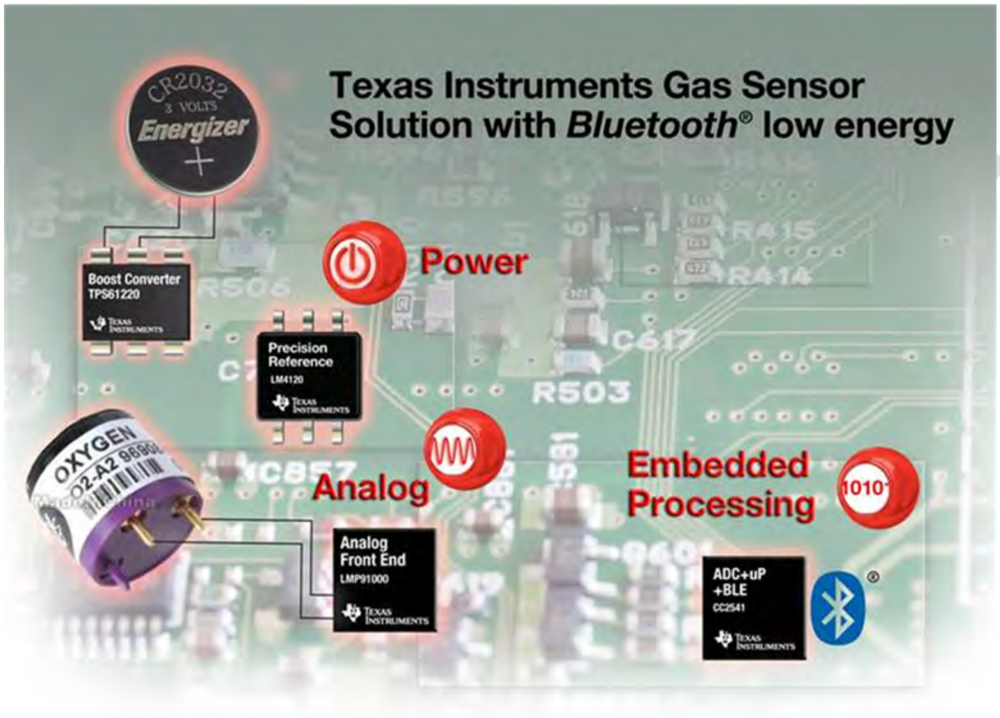


Figure 2-1. Block Diagram of Gas-Sensing Platform With *Bluetooth* Low Energy

Hardware Description

3.1 Getting Started

Requirements:

- Gas sensor: use the recommended CO-AF from Alphasense.
- CR2032: Coin-cell
- An iOS device: iPhone 4S and newer generations; iPad 3 and newer generations; fifth generation iPod (Apple.com).
  Download the (?) application from the Apple App Store™ at iTunes.com.

NOTE: CC-DEBUGGER is the debug tool to load the firmware to CC2541 (ti.com/tool/cc-debugger). The debug tool is needed only if changes to the firmware are required.

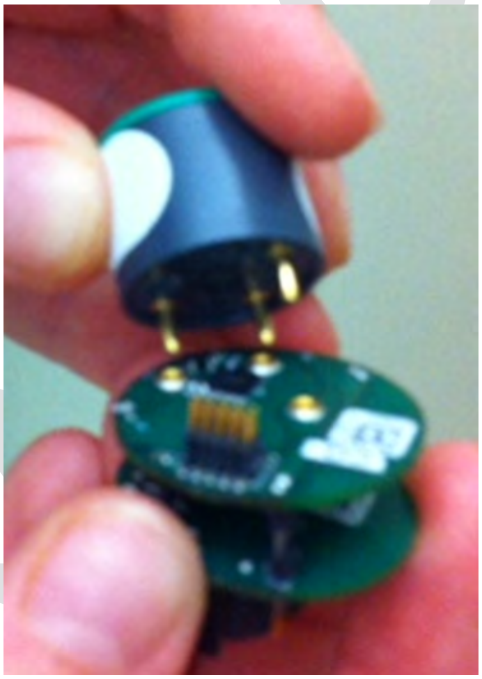


Figure 3-1. Installing the Sensor on the Platform

Figure 3-2. CR2032 Battery

By default the Gas Sensor Platform supports the 3-lead amperometric cell (R43 not installed, see Section 1.3). By default, the firmware and iOS software support the Alphasense CO-AF sensor. TI recommends installing the CO-AF sensor (not included) from Alphasense into the socket on the SAT0010 board (see Figure 3-2).

1. Install the sensor onto the platform (see Figure 3-1).
2. Load the CR2032 (not included in the kit) into the coin-cell holder on the SAT0009 board.
3. Turn the on/off switch to the right (with respect to the orientation shown in Figure 3-3).

NOTE: A blue LED flashes when the default firmware is loaded.

4. Download the application from the App Store.
5. Use an iOS device to access the Gas Sensor Platform and interface with the platform (see Section 7.1).
6. If needed, connect the CC-DEBUGGER (not included in the kit) to the 10-pin header as shown in Figure 3-3. If changes to the default firmware are needed, see Section 7.2.

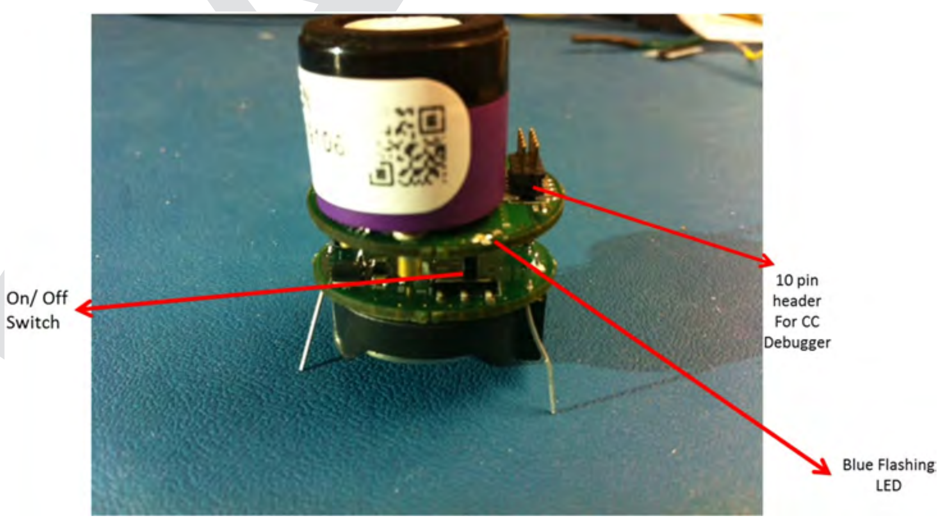


Figure 3-3. System Running With LED Flashing

3.2 Battery Life Calculation

For battery life calculations, it is highly recommended that the customer reviews *CC2541 Battery Life Calculation*, SWRA347.

It is impossible to use a single metric to compare the power consumption of a BLE device to another device. For example, a device gets rated by its peak current. While the peak current plays a part in the total power consumption, a device running the BLE stack only consumes current at the peak level during transmission. Even in very high throughput systems, a BLE device is only transmitting for a small percentage of the total time that the device is connected (see Figure 3-4).

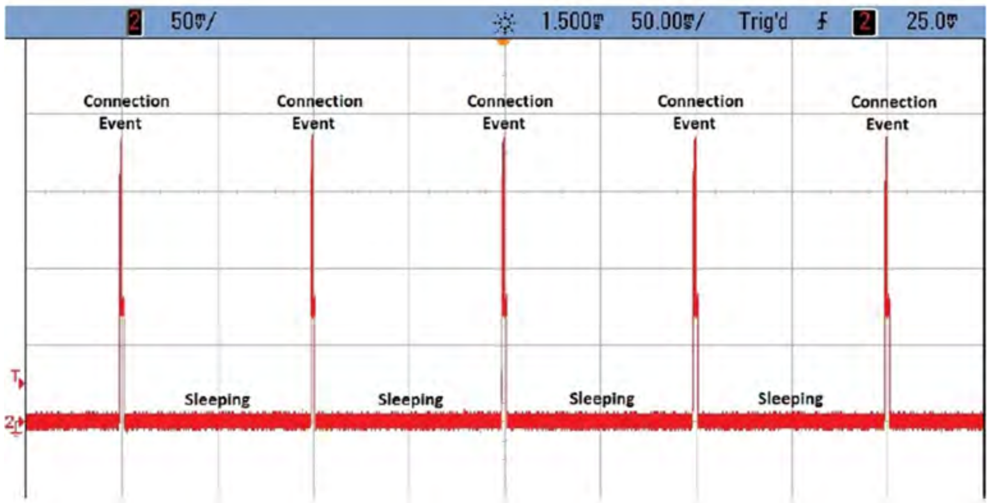


Figure 3-4. Current Consumption

In addition to transmitting, there are other factors to consider when calculating battery life. A BLE device can go through several other states, such as receiving, sleeping, and waking-up from sleep. Even if the current consumption of a device in each different state is known, there is not enough information to determine the total power consumed by the device. Each layer of the BLE stack requires a certain amount of processing to remain connected and to comply with the specifications of the protocol. The MCU takes time to perform this processing, and during this time, current is consumed by the device. In addition, some power might be consumed while the device switches between states (see Figure 3-5). All of this must be considered in order to get an accurate measurement of the total current consumed.

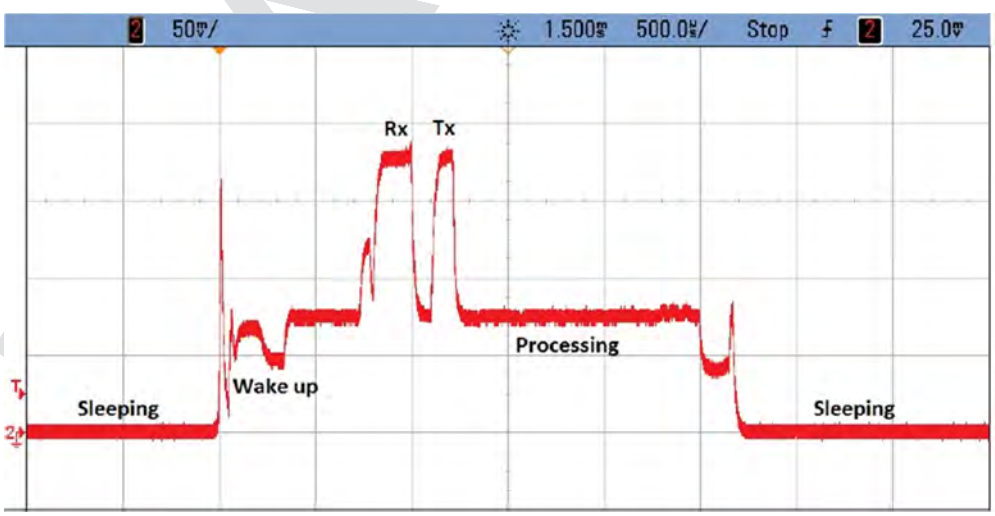


Figure 3-5. Current Consumption-Active vs Sleep Modes

Antenna Simulations

The following data was simulated using the High-Frequency Structural Simulator (HFSS) from ANSYS (www.ansys.com/hfss).

The Gas Sensor Platform with BLE platform is a stackup of two 1-inch diameter boards (see Figure 4-1).

The goals of the antenna simulations include the following:

- Validate that the 2.45-GHz antenna performs as expected.
- Estimate the influence of the battery board, by running simulations with and without the battery board.

4.1 Simulations With the Battery Board (SAT0009)

Both boards were used in the first simulation to determine the affect of the power board (SAT0009) on the BLE antenna located on SAT0010 (see Figure 4-2, Figure 4-3, and Figure 4-4).

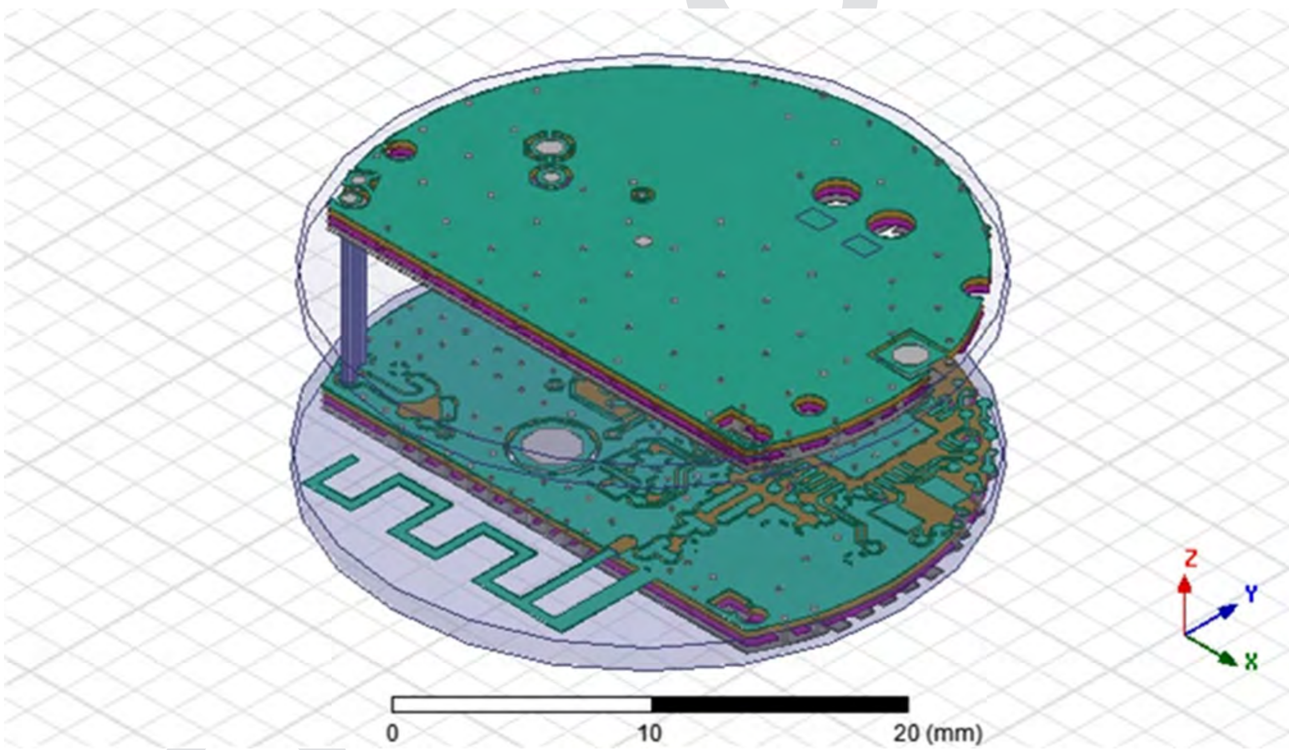
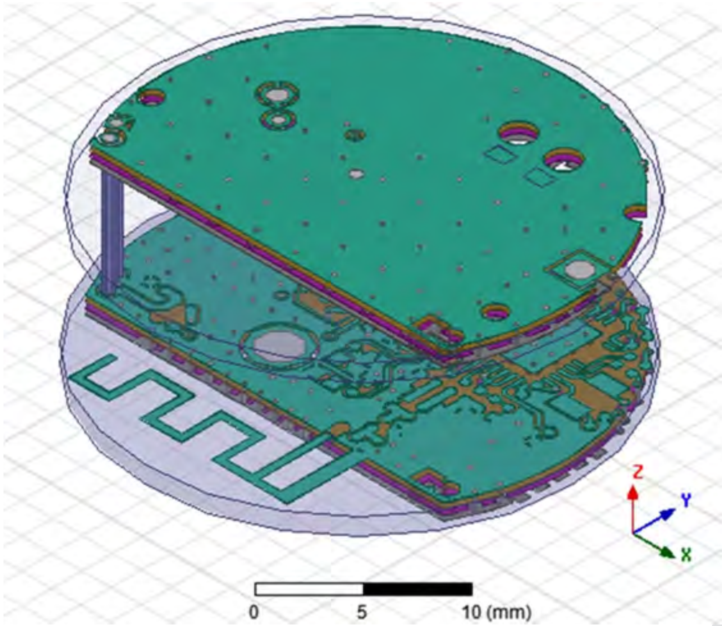


Figure 4-1. Ansoft Antenna Simulation Setup



Antenna Parameters:

Quantity	Value	Units
Max U	0.00039551	W/sr
Peak Directivity	1.1973	
Peak Gain	0.64792	
Peak Realized Gain	0.49703	
Radiated Power	0.0041511	W
Accepted Power	0.0076711	W
Incident Power	0.01	W
Radiation Efficiency	0.54114	
Front to Back Ratio	-N/A-	
Decay Factor	0	

Figure 4-2. Antenna Simulations With Power Board

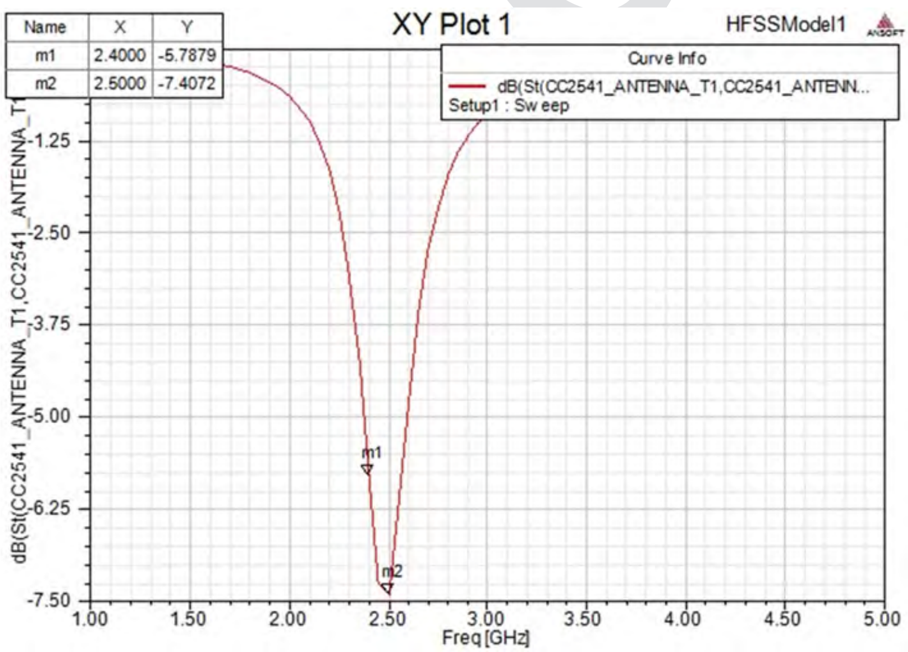


Figure 4-3. Antenna Simulations Matching With Power Board

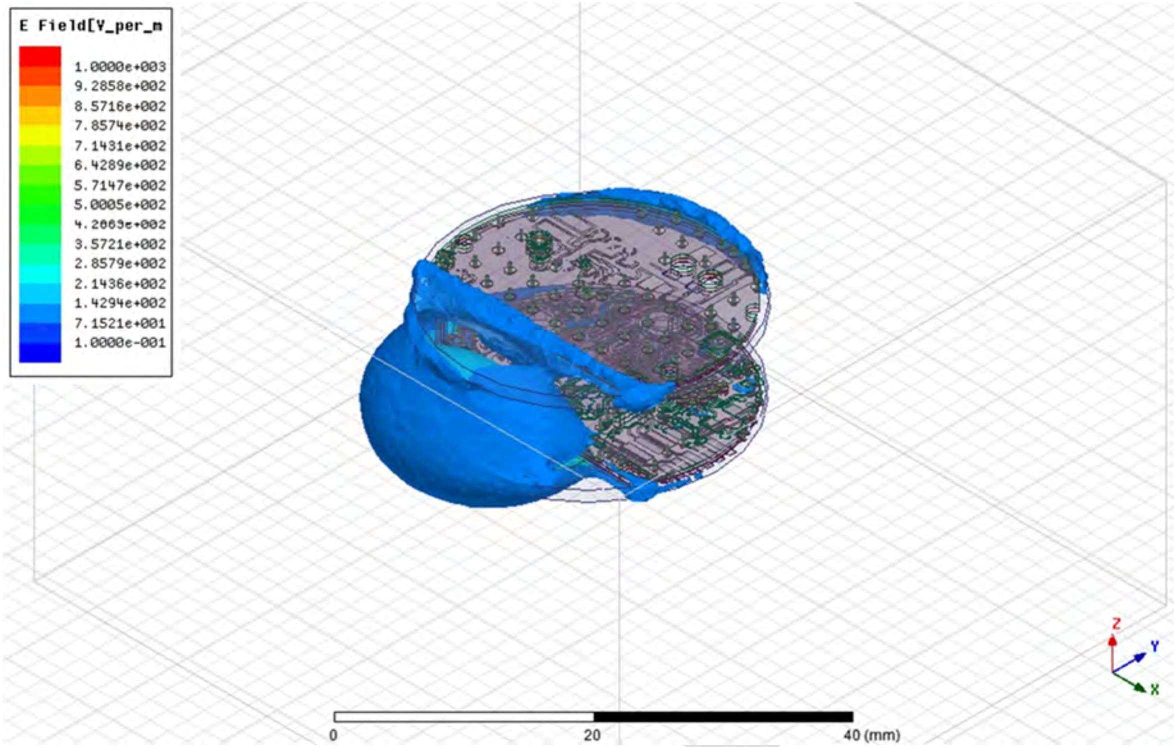


Figure 4-4. Antenna Simulations Electrical Field Propagation With Power Board

The power board (SAT0009) was used in the next simulation to determine if the BLE antenna resulted in an improvement to the performance of SAT0010 (see Figure 4-5, Figure 4-6, and Figure 4-7).

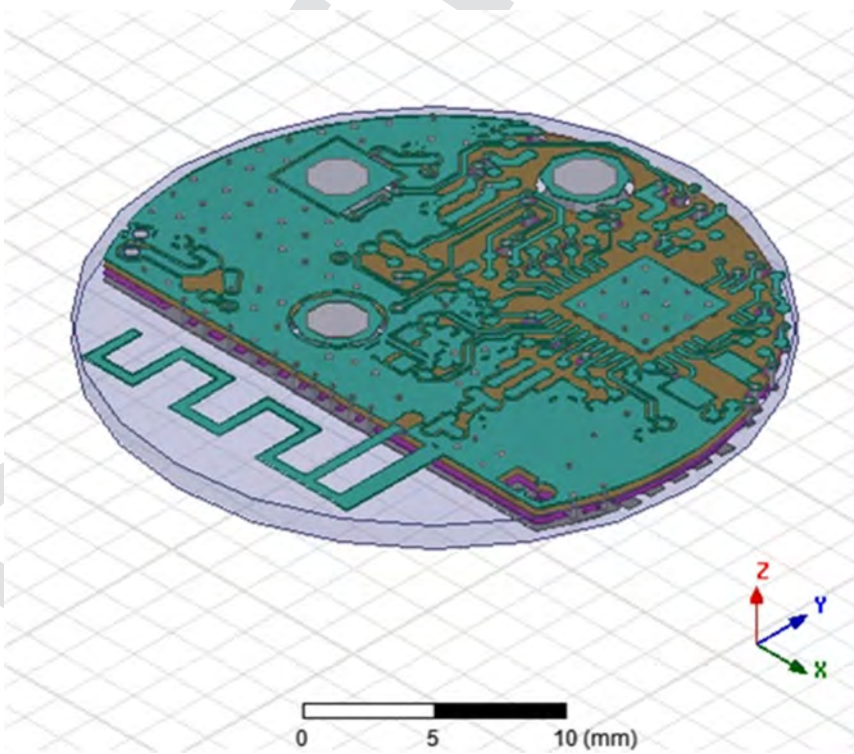


Figure 4-5. Antenna Simulations Setup Without Battery Board

Table 4-1. Antenna Simulations Results Without Battery Board

Quantity	Value	Units
Max U	0.00043244	W/sr
Peak Directivity	1.1138	
Peak Gain	0.66408	
Peak Realized Gain	0.54344	
Radiated Power	0.0048793	W
Accepted Power	0.0081833	W
Incident Power	0.01	W
Radiation Efficiency	0.59625	
Front-to-Back Ratio	Not Applicable	
Decay Factor	0	

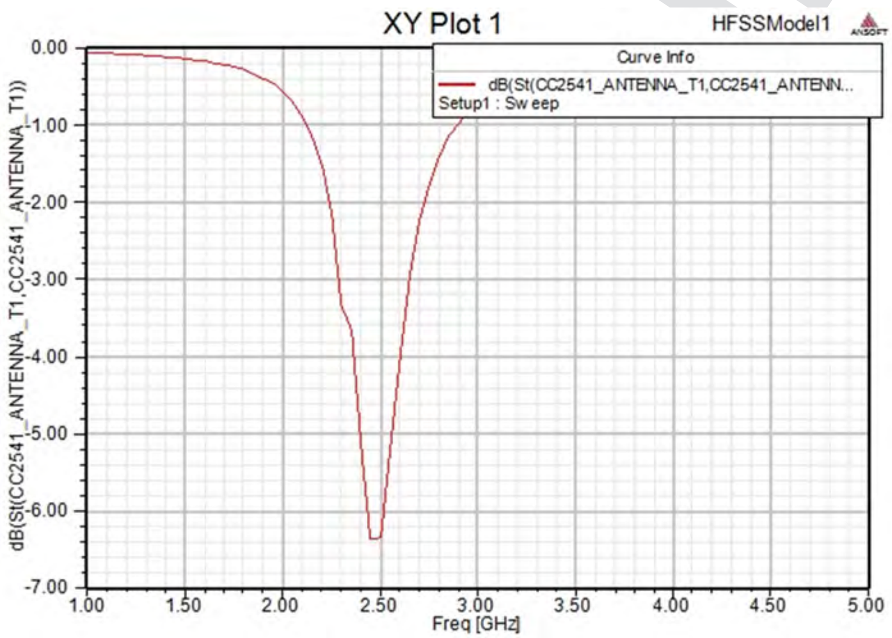


Figure 4-6. Antenna Simulations Matching Without Battery Board

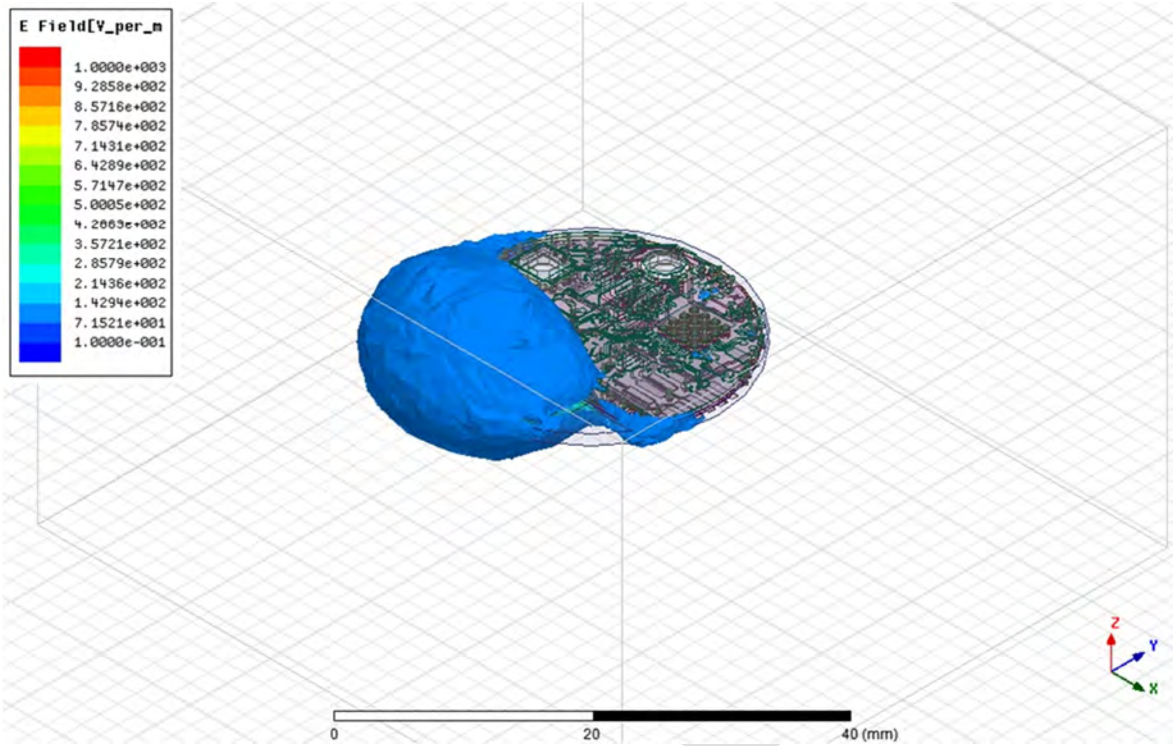


Figure 4-7. Antenna Simulations Field Propagation Without Battery Board

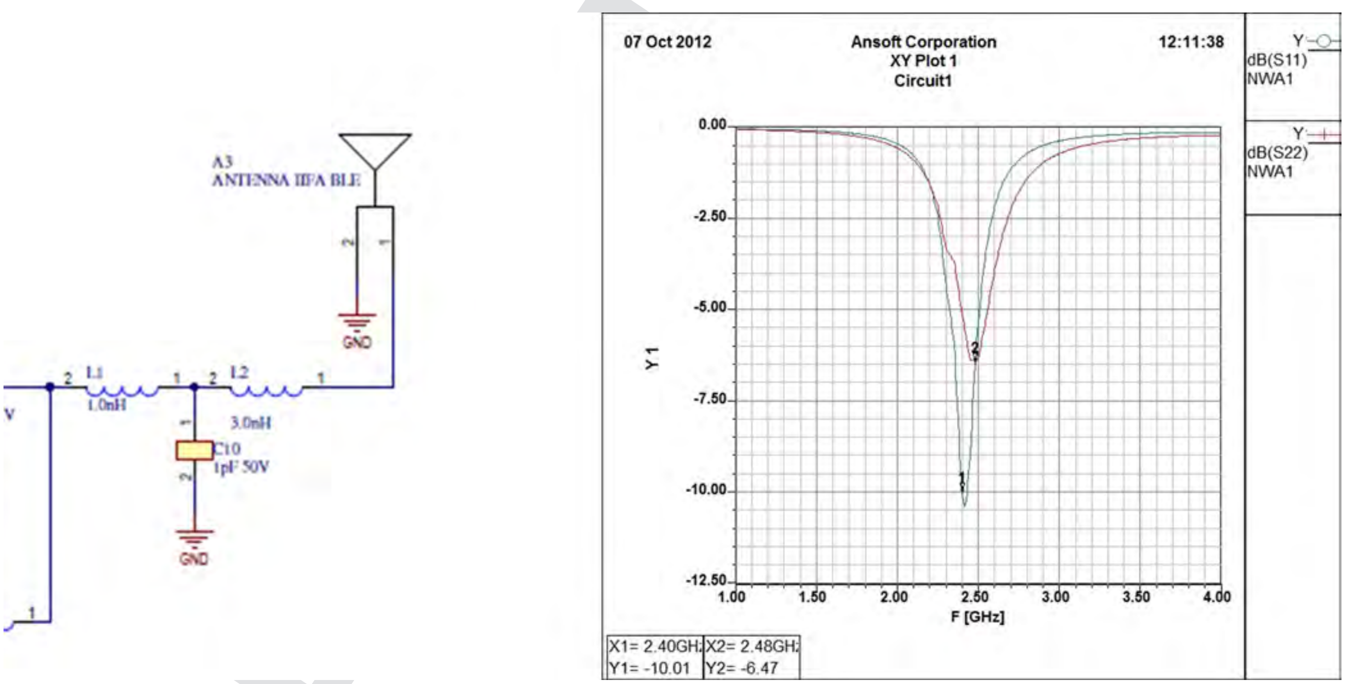


Figure 4-8. Improved Antenna Matching

Antenna matching was improved by increasing the inductor from 3 to 5 nH (see Figure 4-8. The increase resulted in a better return loss value of 10 dB.

4.2 Summary of Findings

- The battery board does not significantly influence the antenna (see Table 4-1).
- Good omnidirectional radiation pattern is found.
  - Low peak gain of 1.2.
- Antenna radiation efficiency is estimated at 54%.

4.3 Conclusion

- Overall board size is very small.
  - Reduces the antenna efficiency from an estimated 70% to 54%.
  - Influences the match of the antenna to become only 6 dB.
- By increasing the last inductor from 3 to 5 nH, the match is improved.

4.4 FCC Reports

The Gas Sensor Platform is compliant with FCC and EU radiation requirements. For additional information, see the following documents:

- *ETSI EN 301 489-17, v2.1.1.* http://processors.wiki.ti.com/index.php/File:10240453EEU1_301_489_report.pdf
- *FCC part 15, subpart B & ICES-003, Issue 4.* http://processors.wiki.ti.com/index.php/File:10240453EUS1_FCC_Report.pdf
- *EN 300 328: v1.7.1.* http://processors.wiki.ti.com/index.php/File:10240453REU1.pdf

Schematics and Bill Of Materials

5.1 SAT Gas Sensor Platform With BLE

5.1.1 Power Board Schematic and BOM

A PDF of the SAT0009 (Power Board) can be found here: http://processors.wiki.ti.com/index.php/File:SAT0009_Rev_E1.pdf.

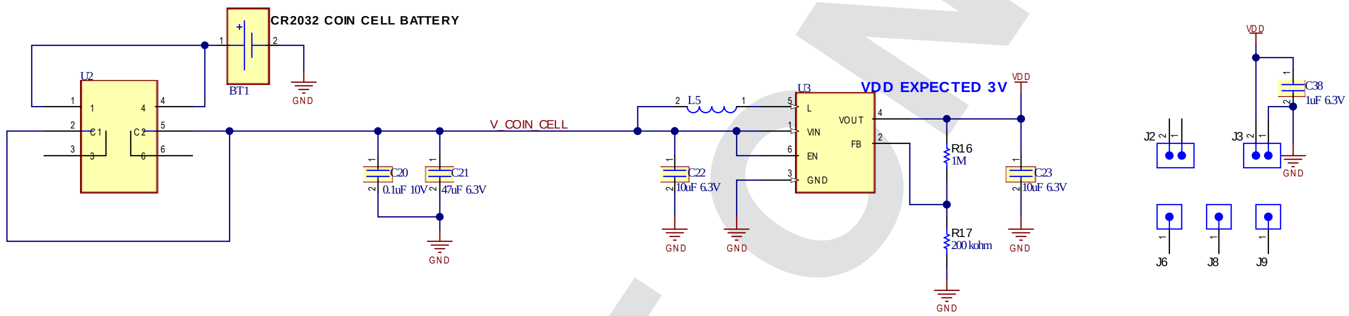


Figure 5-1. Power Section

Table 5-1. Power Section BOM

Comment	Description	Designator	Footprint	LibRef	Qty	Manufacturer	Part No.	Supplier	Part No.
BS-7-ND	Battery Holder	BT1	BATTHOLD-BS-7-CR2032	BS-7-ND	1			Digi-Key	BS-7-ND
GRM155R71A104KA01D	Cap Cer 0.1 µF 10 V 10	C20	C402-25RD	GRM155R71A104KA01	1		GRM155R71A	Digi-Key	GRM155R71A104KA01 D-ND
TSW-101-07-G-S	Conn Header 1POS	C21, J6, J8, J9	JUMP1X1-382650CTR	TSW-101-07-G-S	4	Samtec, Inc.		Digi-Key	SAM1029-01-ND
GRM188R60J106ME47	Cap Cer 10 µF 6.3 V 20	C22, C23	C603-35X45	GRM188R60J106ME47	2		GRM188R60J1	Digi-Key	490-3896-2-ND
GRM155R60J105KE190	Cap Cer 1 µF 6.3 V 10%	C38	C402-25RD	GRM155R60J105KE190	1		GRM155R60J1	Digi-Key	490-1320-2-ND
TBSTC-501-D-200-22-G	Major League Elec 0.05	J2, J3	JUMP1X2-3826-50CTR	TBSTC-501-D-200-22-G	2	Major League	TBSTC-501-D-2		
EPL3015	Power Inductor, Shielder	L5	EPL3015-INDUCTOR	EPL3015	1	Coilcraft	EPL3015-427M		
CRCW04021M00JNED	RES 1.0 mΩ 1/6W	R16	R402-25RD	CRCW04021M00JNED	1			Digi-Key	541-1.0MJCT-ND
CRCW0402200KJNED	Res 200 KΩ 1/6W	R17	R402-25RD	CRCW0402200KJNED	1			Digi-Key	541-200KJDKR-ND
EG1390B		U2	EG1390-SWITCH	EG1390B	1			Digi-Key	EG4633TR-ND
TPS6120DCK		U3	DCK6	TPS61220DCK	1			Digi-Key	296-32505-2-ND

5.2 BLE and AFE Section

A PDF of the SAT0010 AFE (LMP91000) and BLE (CC2541) can be found here: http://processors.wiki.ti.com/index.php/File:SAT0010_Rev_E1.pdf.

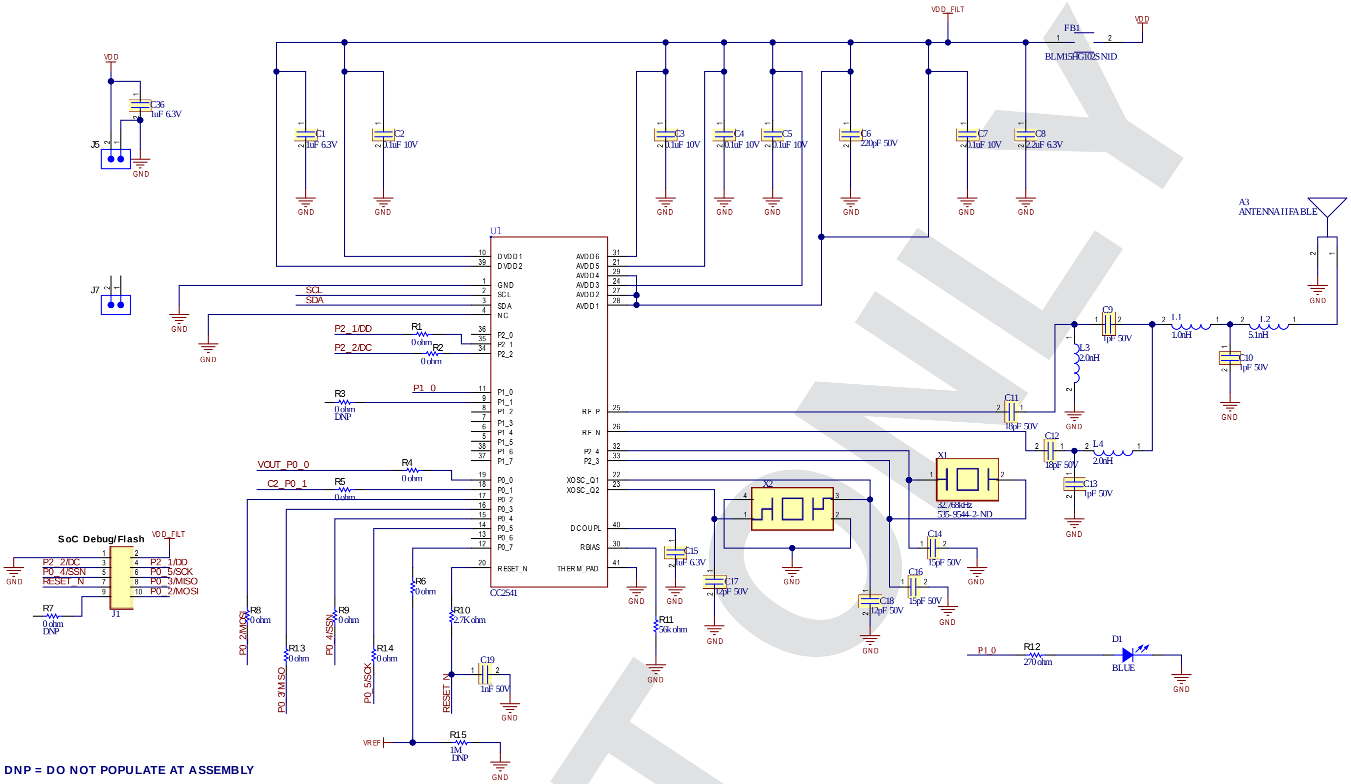
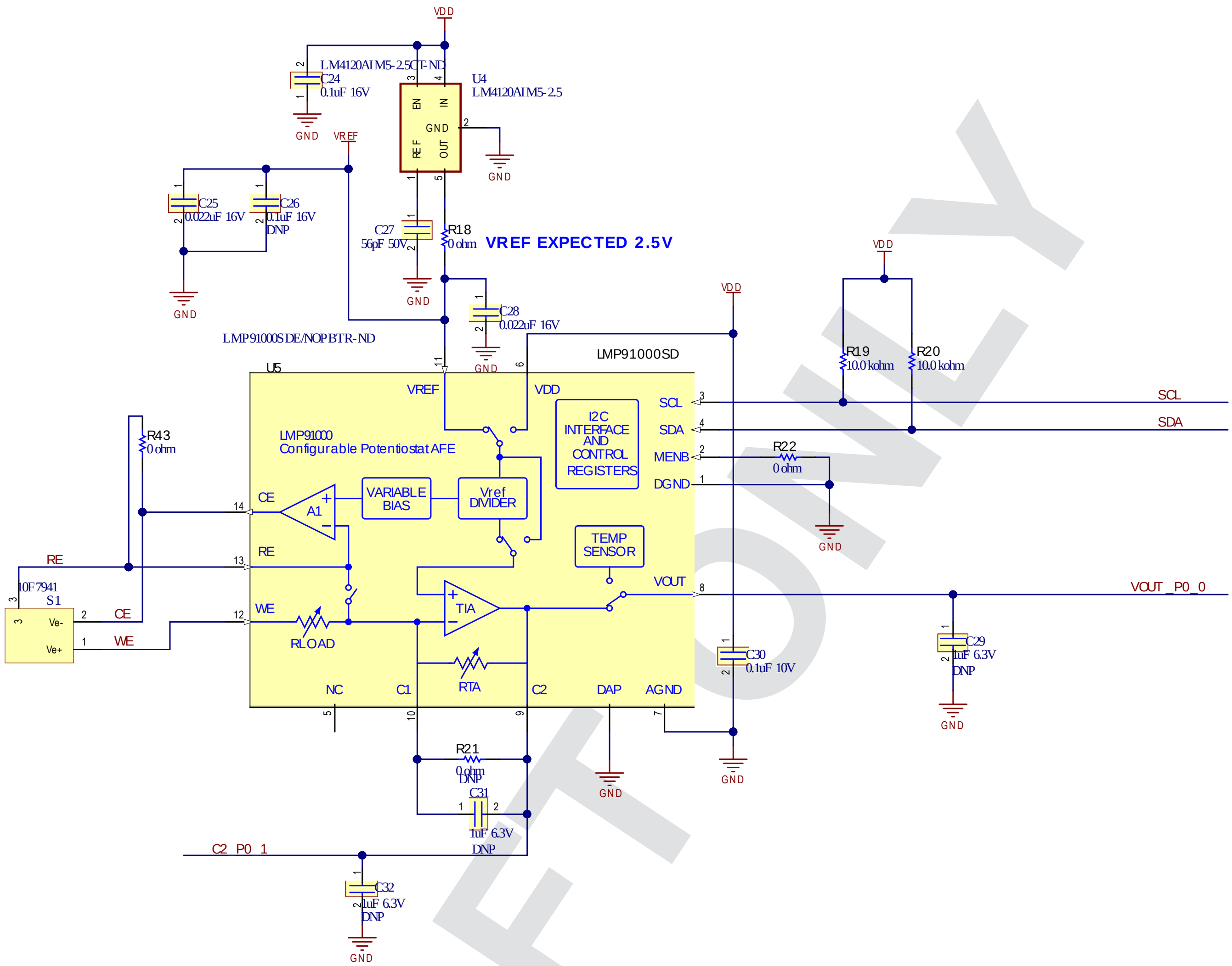


Figure 5-2. BLE Section



DNP = DO NOT POPULATE AT ASSEMBLY

Figure 5-3. AFE Section

Table 5-2. BLE Section BOM

Comment	Description	Designator	Footprint	LibRef	Qty	ASSY_Option	Manufacturer	Part No.	Supplier	Part No.
ANTENNA IIFA BLE	Antenna IIFA BLE	A3	Antenna_IIFA_BLE	Antenna	1	No part to order or place at ASSY				
GRM155R60J105KE19D	Cap Cer 1 µF 6.3 V 10% X5R	C1, C15, C36	C402-25RD	GRM155R60J105KE19D	3			GRM155R60J105KE19D	Digi-Key	490-1320-2-ND
GRM155R71A104KA01D	Cap Cer 0.1 µF 10 V 10% X7R	C2, C3, C4, C5, C7, C30	C402-25RD	GRM155R71A104KA01D	6			GRM155R71A104KA01D	Digi-Key	GRM155R71A104KA01D-ND
GRM1555C1H221JA01D	Cap Cer 220 pF 50 V 5% NP0	C6	C402-25RD	GRM1555C1H221JA01D	1			GRM1555C1H221JA01D	Digi-Key	490-1293-2-ND
GRM155R60J225ME15D	Cap Cer 2.2 µF 6.3 V 20% X5R	C8	C402-25RD	GRM155R60J225ME15D	1			GRM155R60J225ME15D	Digi-Key	490-4519-1-ND
GRM1555C1H1R0CA01D	Cap Cer 1 pF 50 V NP0	C9, C10, C13	C402-25RD	GRM1555C1H1R0CA01D	3			GRM1555C1H1ROCA01D	Digi-Key	490-3199-2-ND
GRM1555C1H180JZ01D	Cap Cer 18 pF 50 V 5% NP0	C11, C12	C402-25RD	GRM1555C1H180JZ01D	2			GRM1555C1H180JZ01D	Digi-Key	490-1281-2-ND
GRM1555C1H150JA01D	Cap Cer 15 pF 50 V 5% NP0	C14, C16	C402-25RD	GRM1555C1H150JA01D	2			GRM1555C1H150JA01D	Digi-Key	490-5888-2-ND
GRM1555C1H120JA01D	Cap, 0402, C0G, 50 V, 12 pF	C17, C18	C402-25RD	GRM1555C1H120JA01D	2			GRM1555C1H120JA01D	Newark	14T3292
GRM1555C1H102JA01D	Cap Cer 1000 pF 50 V 5% NP0	C19	C402-25RD	GRM1555C1H102JA01D	1			GRM1555C1H102JA01D	Digi-Key	490-324-2-ND
C0402C104K4RAC7411	Cap Cer 0.1 µF 16 V 10% X7R	C24	C402-25RD	C0402C104K4RAC7411	1			C0402C104K4RAC7411	Digi-Key	399-7352-2-ND
GRM155R71C223KA01J	Cap Cer 0.022 µF 16 V 10% X7R	C25, C28	C402-25RD	GRM155R71C223KA01J	2		Johanson Dielectrics Inc.	GRM155R71C223KA01J	Digi-Key	709-1128-2-ND
C0402C104K4RAC7411	Cap Cer 0.1 µF 16 V 10% X7R	C26	C402-25RD	C0402C104K4RAC7411	1	DNP		C0402C104K4RAC7411	Digi-Key	399-7352-2-ND
VJ0402D560JXAAJ	Cap Cer 56PF 50 V 5% NP0	C27	C402-25RD	VJ0402D560JXAAJ	1			VJ0402D560JXAAJ	Digi-Key	720-1293-2-ND
GRM155R60J105KE19D	Cap Cer 1UF 6.3 V 10% X5R	C29, C31, C32	C402-25RD	GRM155R60J105KE19D	3	DNP		GRM155R60J105KE19D	Digi-Key	490-1320-2-ND
LED 0402 BLUE 465NM TRANSPARENT		D1	LED-SML-31SQ	LED 0402 BLUE465NM TRANSPARENT	1				Digi-Key	511-1615-1-ND
BLM15HG102SN1D	Filter Chip 1000 Ω 250 mA	FB1	I402-25	BLM15HG102SN1D	1			BLM15HG102N1D	Digi-Key	490-3999-2-ND
FTSH-105-01-FDH		J1	FTSH2X5-110X29	FTSH-105-01-FDH	1				Arrow	2745567S5787043N1004
TBSTC-501-D- 200-22-G-300-LF	Major League Elec .050x.050 cl Thicker Brd Stacker Term Strips - Custom	J5, J7	JUMP1X2-3826-50CTR	TBSTC-501-D- 200-22-G-300- LF	2		Major League Elec	TBSTC-501-D-200-22-G-300-LF		
LQG15HS1N0S02D	1 nH, I0402-25	L1	I402-25	LQG15HS1N0S02D	1		Murata Elec	LQG15HS1N0S02D	Digi-Key	490-2610-2-ND
LQG15HH5N1S02D	5.1 nH ±0.3 nH, I0402-25	L2	I402-25	LQG15HH5N1S02D	1		Murata Elec	LQG15HH5N1S02D	Mouser	81-LQG15HH5N1S02D
LQG15HS2N0S02D	2.0 nH, I0402-25	L3, L$	I402-25	LQG15HS2N0S02D	2		Murata	LQG15HS2N0S02D	Mouser	81-LQG15HS2N0S02D

Table 5-2. BLE Section BOM (continued)

Comment	Description	Designator	Footprint	LibRef	Qty	ASSY_Option	Manufacturer	Part No.	Supplier	Part No.
ERJ-2GE0R00X	Res 0 Ω 1/10W	R1, R2, R4, R5, R6, R8, R9, R13, R14, R18, R22, R43	R402-25RD	ERJ-2GE0R00X	12				Digi-Key	P0.0JTR-ND
ERJ-2GE0R00X	Res 0 Ω 1/10W	R3, R21	R402-25RD	ERJ-2GE0R00X	2	DNP			Digi-Key	P0.0JTR-ND
CR0402-J/-000G	Resistor Chip, Jumper, 0 Ω, 1%	R7	R402-25RD	CR0402-J/-000G	1	DNP			Newark	02J1955
CRCW04022K70FKED	Res 2.70 KΩ 1/16W 1%	R10	R402-25RD	CRCW04022K70FKED	1				Digi-Key	541-2.70KLCT-ND
CRCW040256K0FKED	Res 56 KΩ 1/16W 1%	R11	R402-25RD	CRCW040256K0FKED	1				Digi-Key	541-56.0KLCT-ND
CRCW0402270RFKED	Res 270 Ω 1/16W 1%	R12	R402-25RD	CRCW0402270RFKED	1				Digi-Key	541-270LCT-ND
CRCW04021M00JNED	Res 1 mΩ 1/16W 5%	R15	R402-25RD	CRCW04021M00JNED	1	DNP			Digi-Key	541-1.0MJCT-ND
CRCW040210K0FKED	Res 10 KΩ 1/16W 1%	R19, R20	R402-25RD	CRCW040210K0FKED	2				Digi-Key	541-10.0KLCT-ND
Socket and Oxygen-Sensor		S1	SKT_O2-A1	Socket and Oxygen-Sensor	1		Alphasense (Sensor)	02-A1	Newark	10F7941
							Cambion (Socket)	450-3326-01-03-00		
CC2541	Single Chip BLE	U1		CC2541	1		TI	CC2541F256RHAR		
LM4120AIM5- 2.5/NOPB	IC VREF Series Prec 2.5 V	U4	SOT23-27X39-5	LM4120AIM5-2.5/NOPB	1				Digi-Key	LM4120AIM5-2.5CT-ND
LMP91000SD	Configurable AFE Potentiostat for Low-Power Chemical Sensing	U5	NHL0014B-WSON	LMP91000SD	1		TI		Digi-Key	LMP91000SDE/NOPBTR-ND
ABS07- 32.768kHz-9	Oscillator	X1	XTAL2-ABS07	ABS07-32.768kHz-9	1				Digi-Key	535-9544-2-ND
FA128	Oscillator	X2	XTAL4-37X34-FA128	FA128	1		Epson	Q22FA1280009200		

NOTE: Capacitors C29 and C32 on SAT0010 provide low-pass filtering to the analog output signals (Vout and C2) from LMP91000. In the schematic, they are placed as placeholders and shown as DNP (Do not populate). During testing of this platform it was noted that a value of .01 µF was most optimized for C29 and C32 for this particular platform. Customers can fine-tune this selection based on their system design.

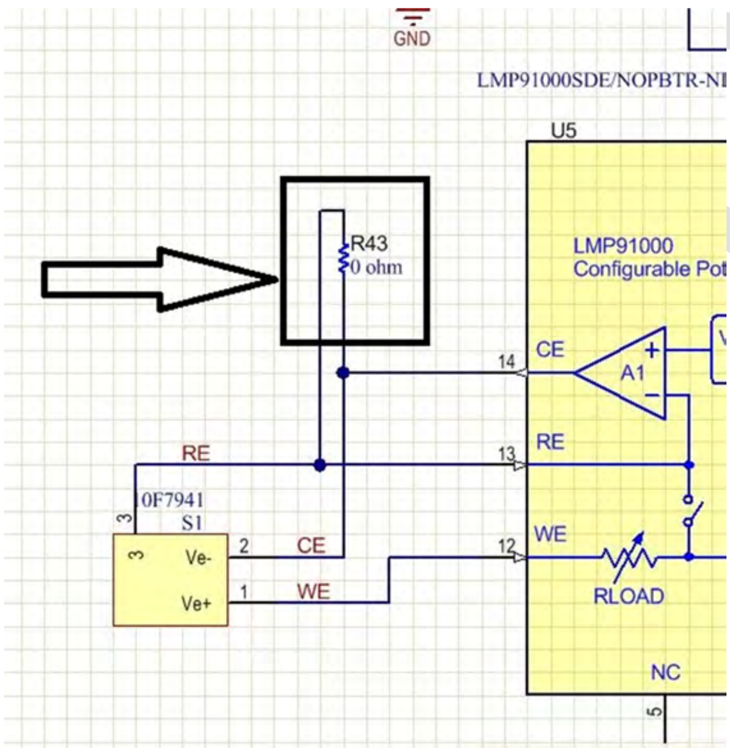


Figure 5-4. CO - O_2

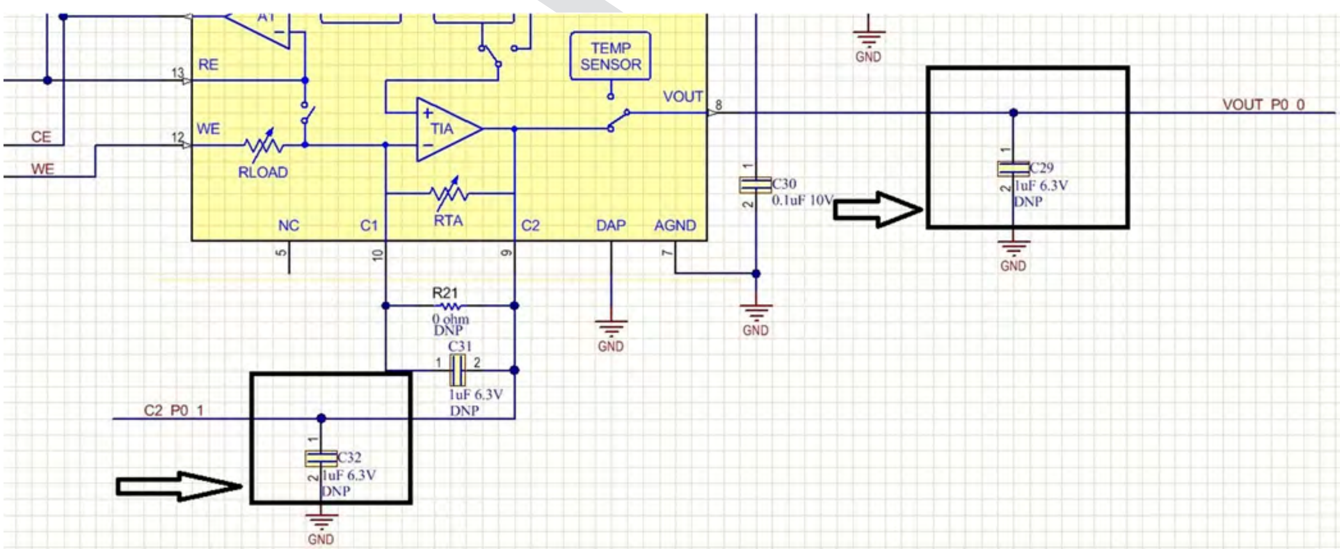


Figure 5-5. Filter

Layout

6.1 SAT Gas Sensor Platform With BLE

6.1.1 SAT0009 (Power Board) Layer Plots

A PDF of the SAT0009 (power board) layer plots can be found here: http://processors.wiki.ti.com/index.php/File:SAT0009_Layer_Plot.PDF.

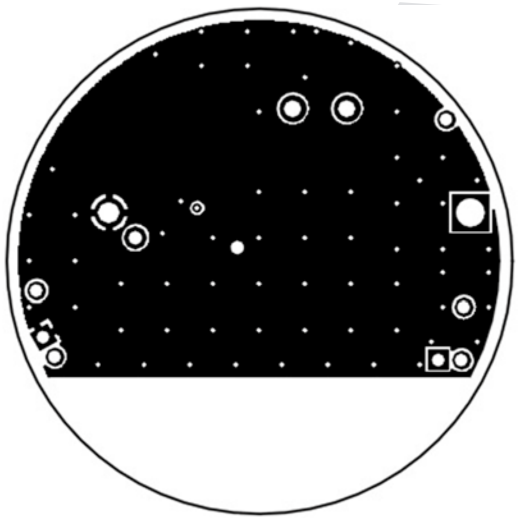


Figure 6-1. Power Board

6.1.2 SAT0010 (AFE and BLE Board) Layer Plots

A PDF of the SAT0010 (AFE and BLE board) layer plots can be found here: http://processors.wiki.ti.com/index.php/File:SAT0009_Layer_Plot.PDF.

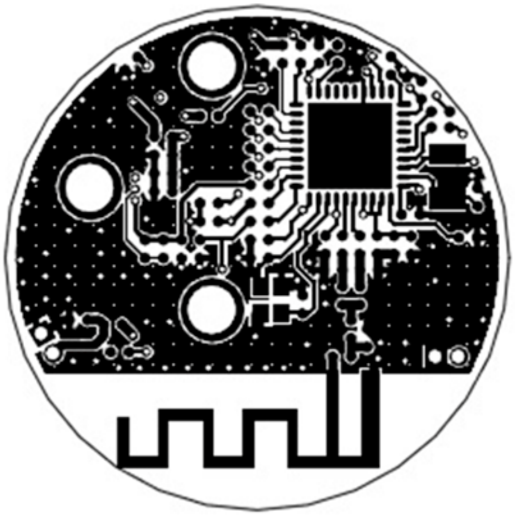


Figure 6-2. BLE and AFE Board

Practical Applications

7.1 iOS Application

Figure 7-1, Figure 7-2, Figure 7-3, Figure 7-4, and Figure 7-5 show the TI BLE Sensor application as used with an iPad.

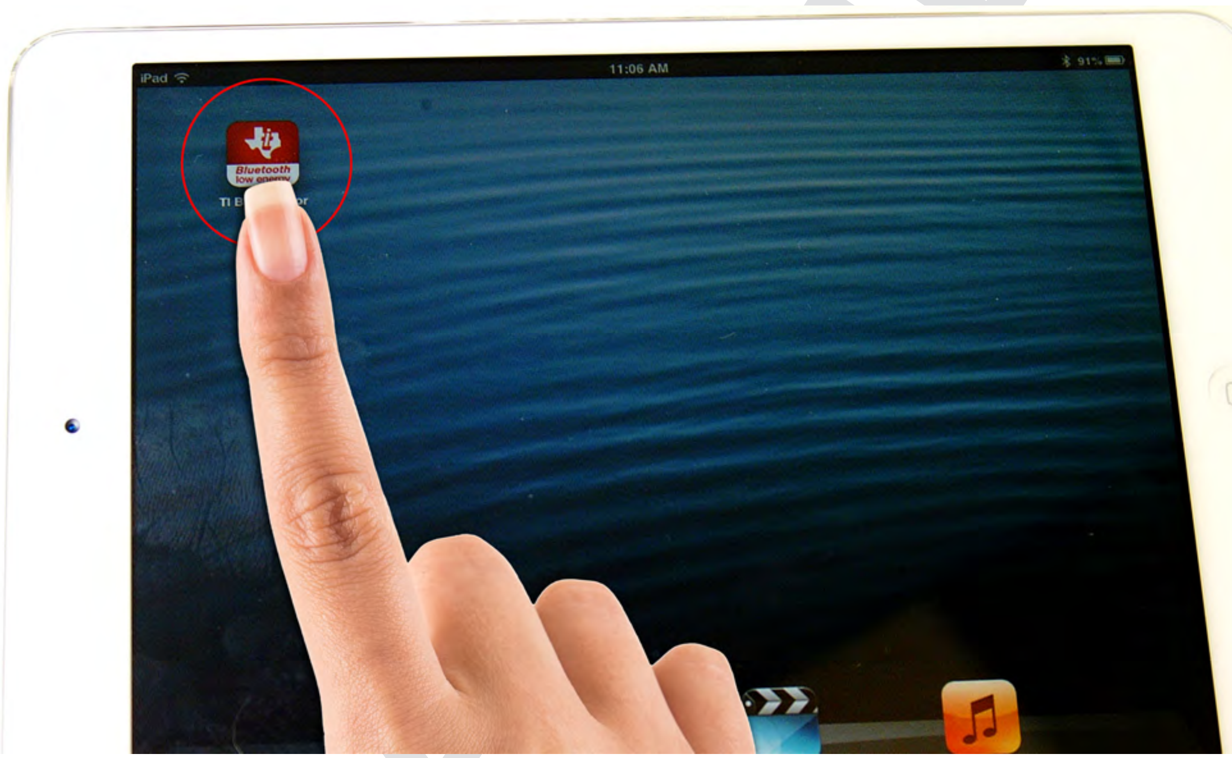


Figure 7-1. Application Icon

Figure 7-2. Locating the Sensors

Figure 7-3. Updating the Sensors

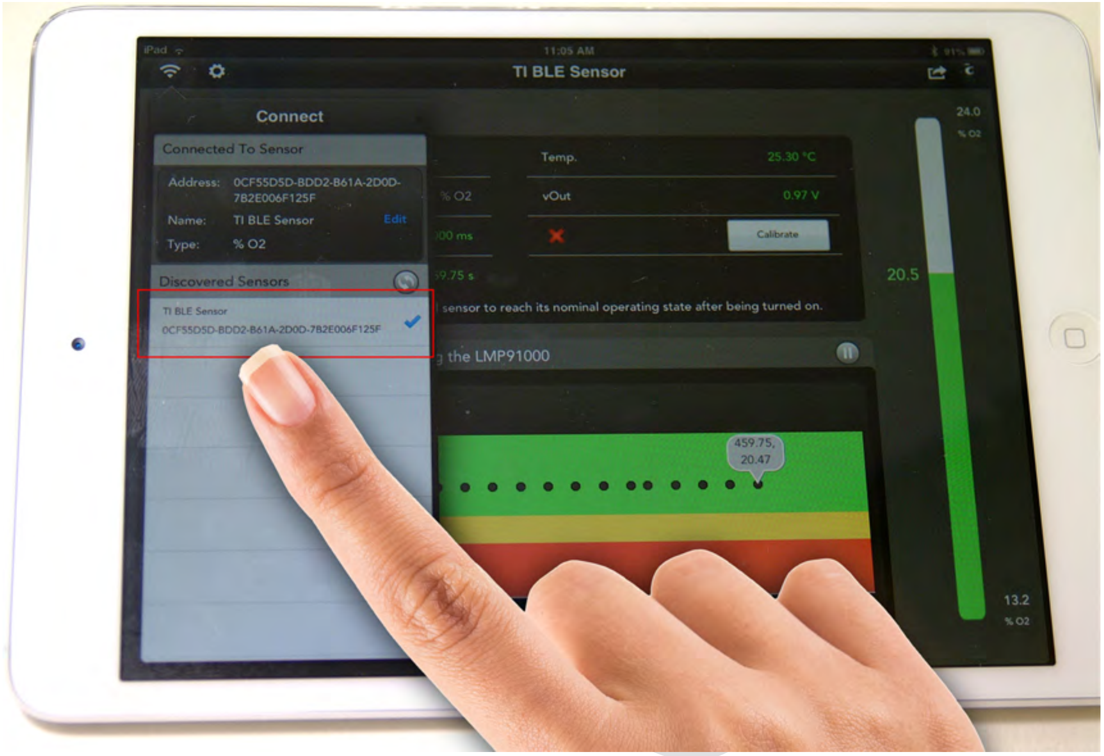


Figure 7-4. Connecting to a Sensor

Figure 7-5. Main Menu

7.2 Firmware Section

One of the development platforms for the CC2451 8051 microcontroller is the IAR development platform. See http://www.iar.com/ for information on this platform.

To communicate to the development platform through IAR, the CC Debugger is required. See Section 3.1.

The CC Debugger must be connected to the 10-pin header on the SAT0010 board. Make sure that the notch on the cable that connects to the 10-pin header is facing away from the sensor or toward the outside. If connected properly, the LED on the CC Debugger should turn green.

Figure 7-6. CC Debugger

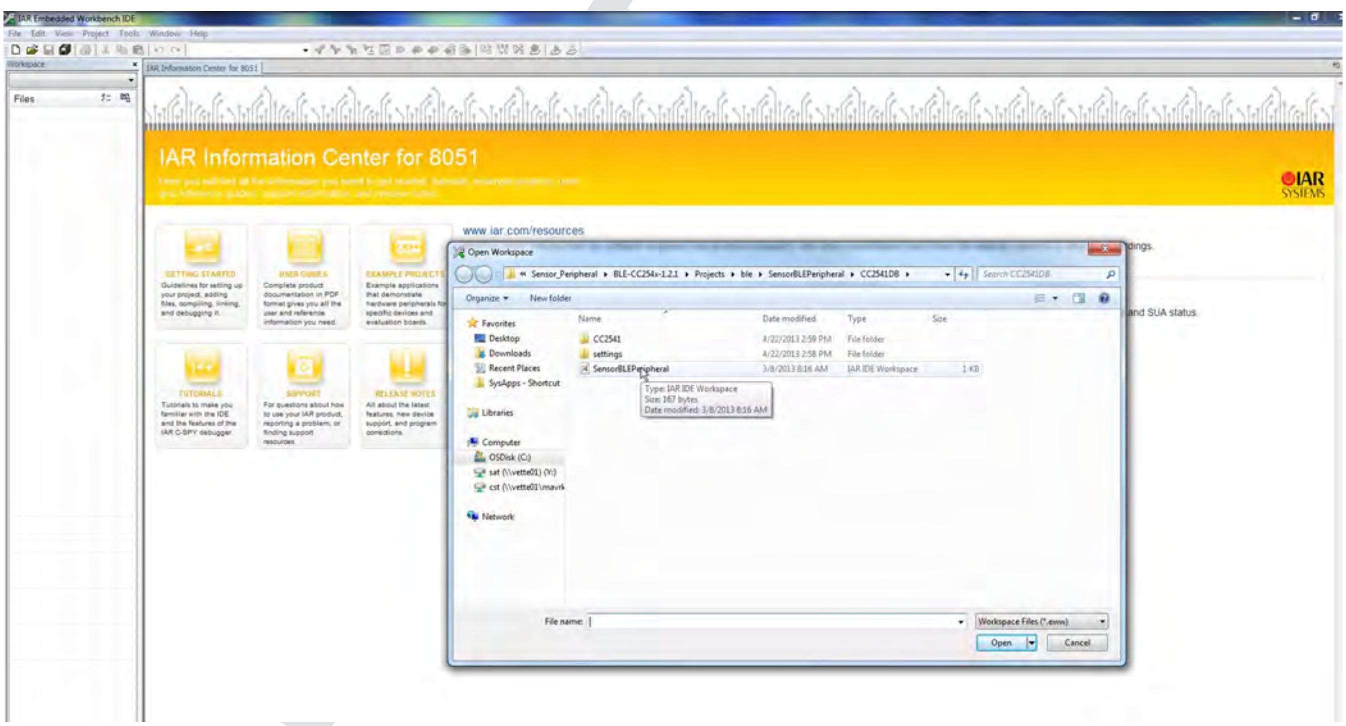


Figure 7-7. Launching IAR

Launch the project file as shown in Figure 7-7.

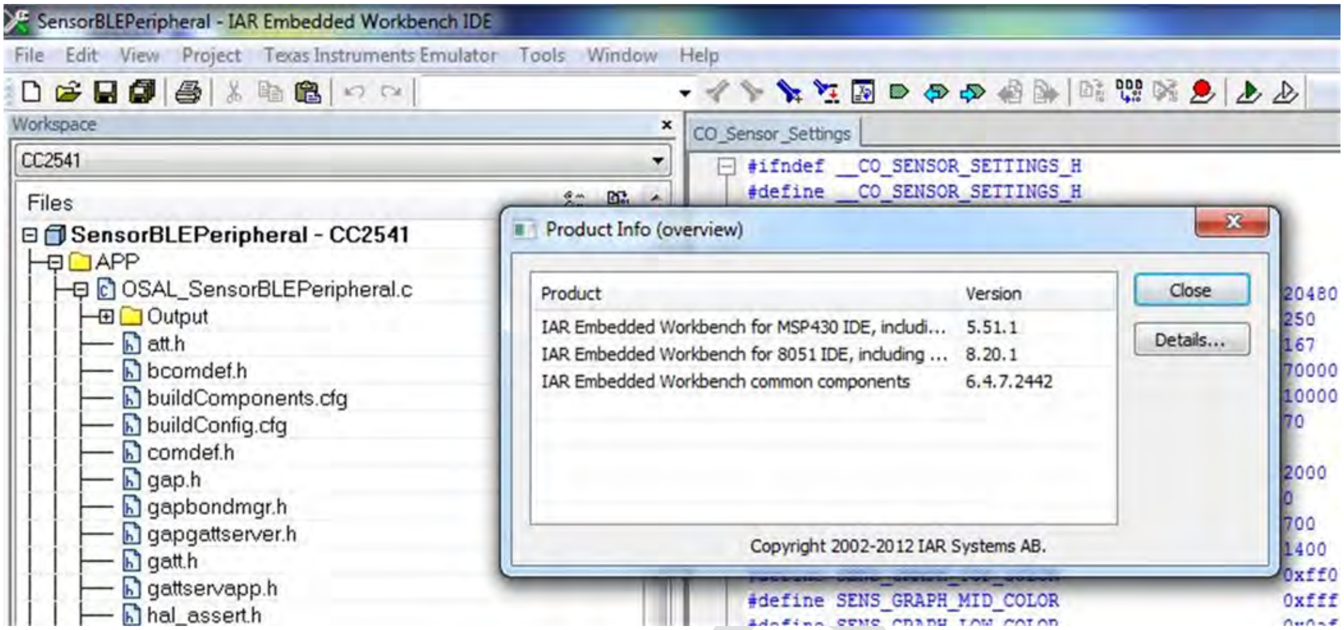


Figure 7-8. IAR Version in Use

Ensure that you are using the version used in Figure 7-8 or a newer version.

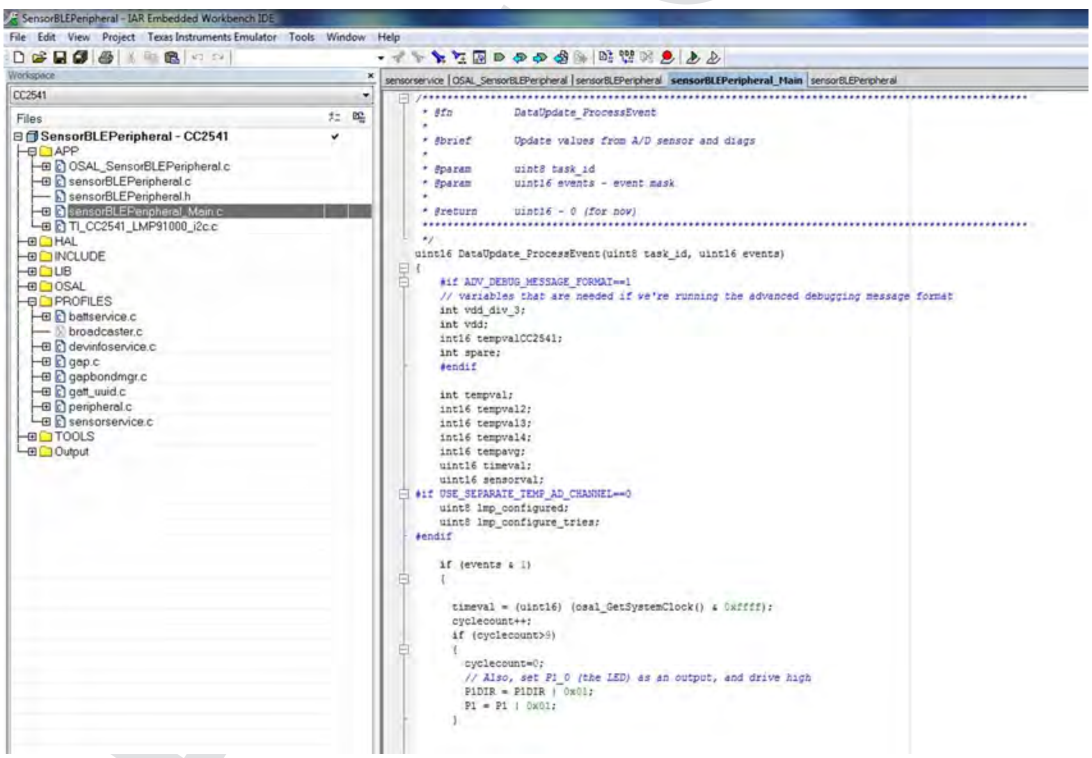


Figure 7-9. Main Loop

Highlight Main.c, as shown in Figure 7-9.

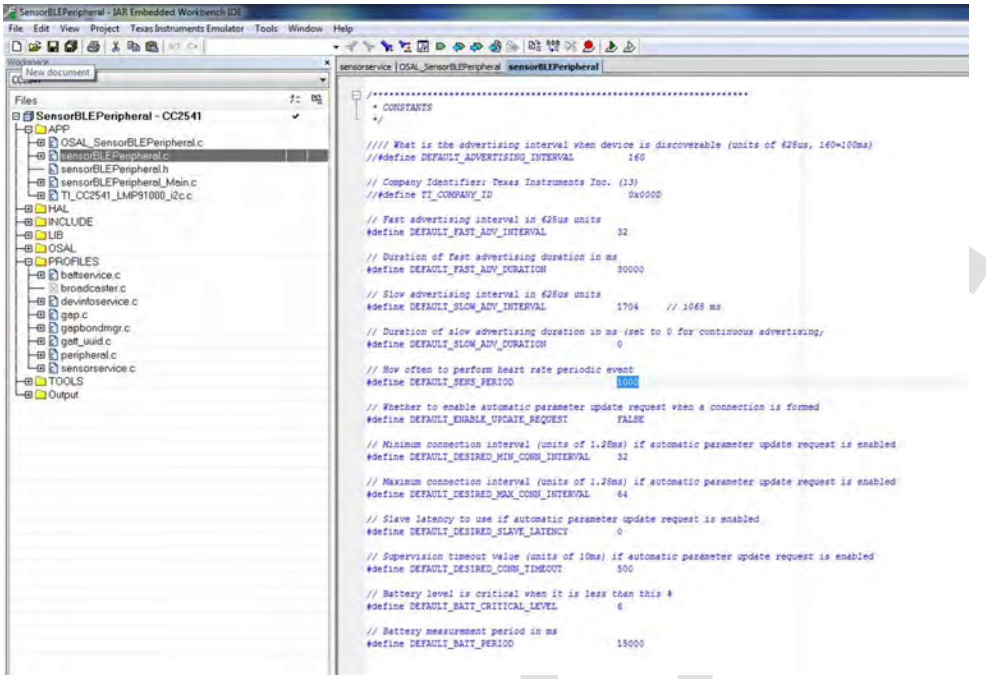


Figure 7-10. Communication Settings

The number of times the *Bluetooth* radio communicates with the iOS application can be easily changed by using the highlighted variable shown in Figure 7-10.

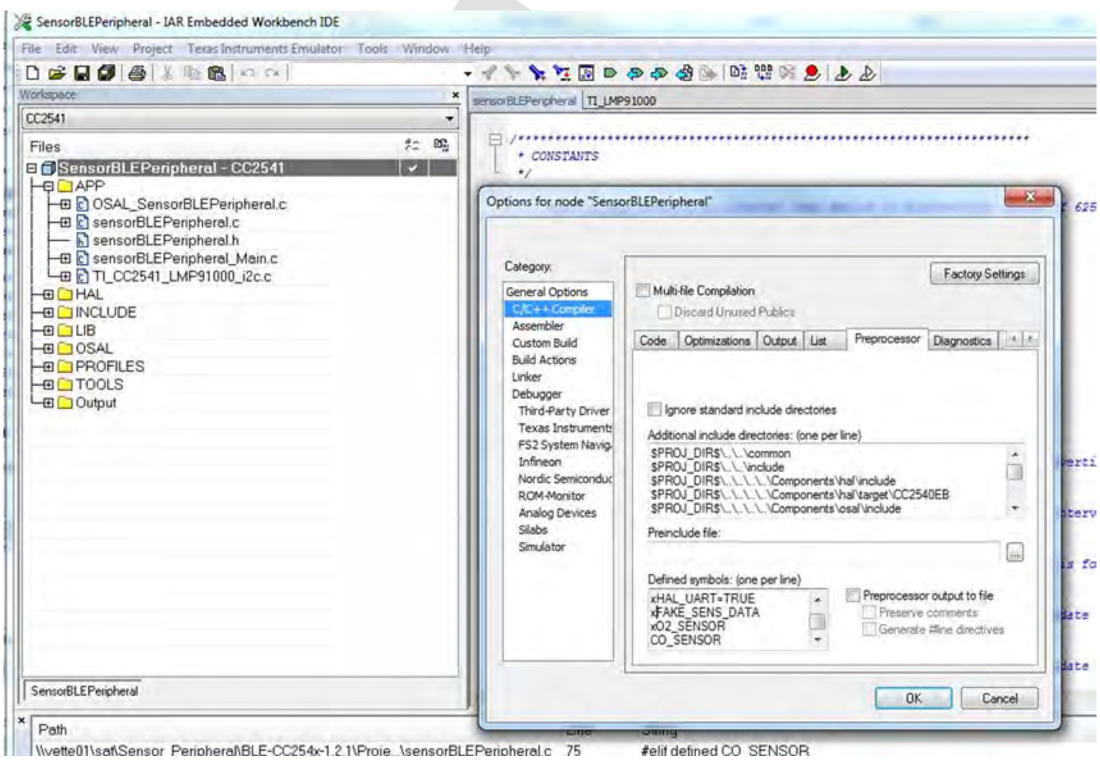


Figure 7-11. Sensor Section

The firmware has a case statement to easily change from a CO sensor to an O_2 sensor, as shown in Figure 7-11. Note the x in front of the CO option.

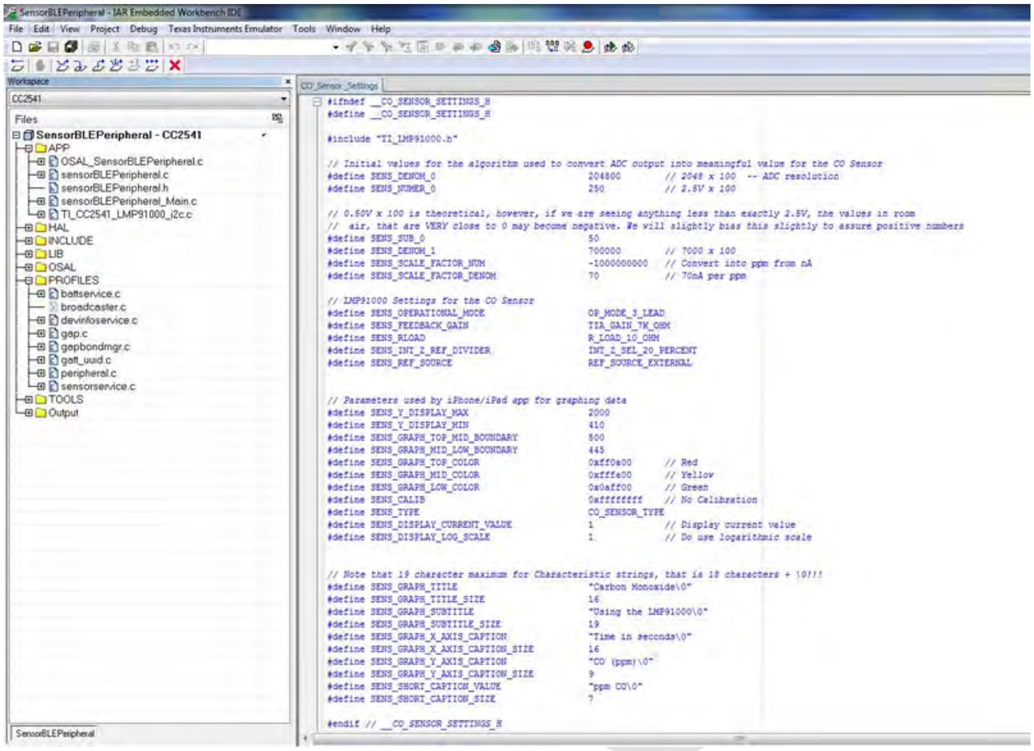


Figure 7-12. CO Settings

All the key configuration settings for LMP91000 have been co-located for easy update to the firmware (see Figure 7-12).

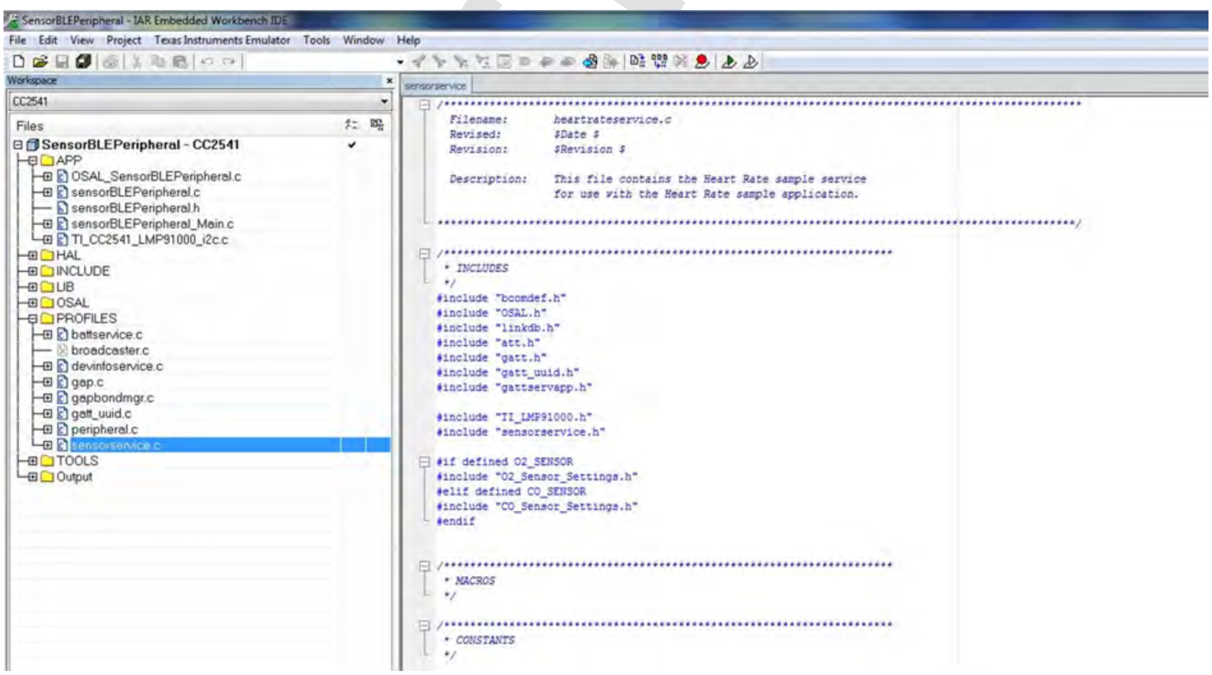


Figure 7-13. Adding New Sensor

New sensor services can be added to the firmware, as shown in Figure 7-13.

SAT0009 Power Board Files

A.1 Gerber Files

The .zip file for the SAT0009 power board can be found here:
http://processors.wiki.ti.com/index.php/File:SAT0009_Rev_E1(Gerbers,_TPS61220)121008A.zip.

The .zip file for the SAT0010 AFE and BLE board can be found here:
http://processors.wiki.ti.com/index.php/File:SAT0009_Rev_E1(Gerbers,_TPS61220)121008A.zip.

A.2 Altium Project Files

The .zip file for the SAT0009 power board can be found here:
http://processors.wiki.ti.com/index.php/File:SAT0009_Layer_Plot.PDF.

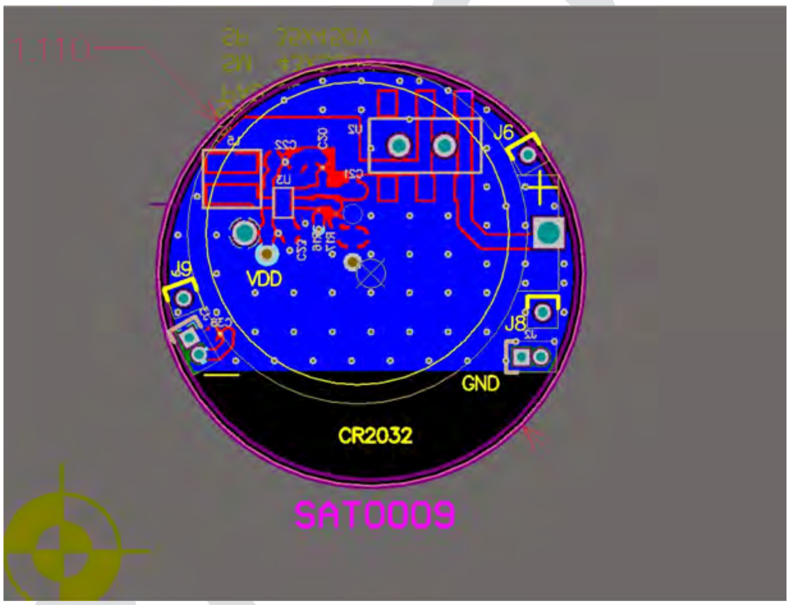


Figure A-1. Power Board

The .zip file for the SAT0010 AFE and BLE board can be found here:
http://processors.wiki.ti.com/index.php/File:SAT0009_Layer_Plot.PDF.

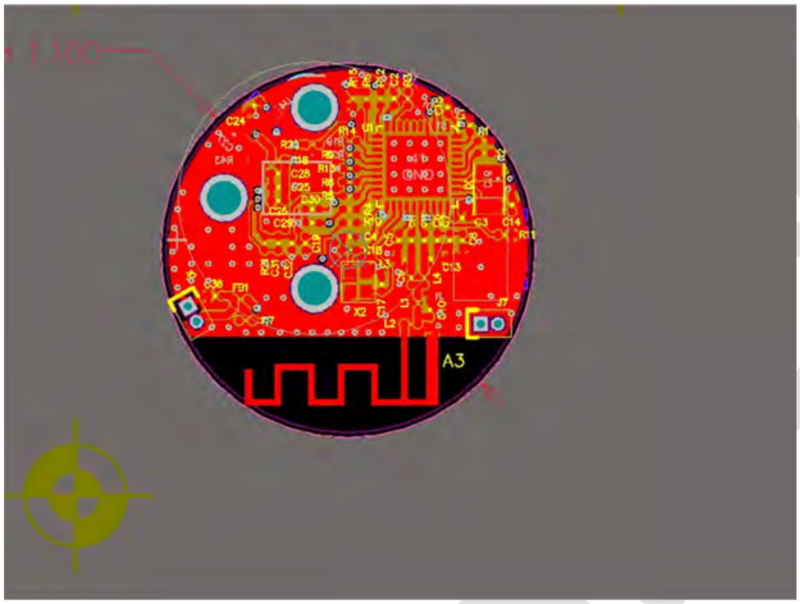


Figure A-2. AFE and BLE Board

EVALUATION BOARD/KIT/MODULE (EVM) ADDITIONAL TERMS

Texas Instruments (TI) provides the enclosed Evaluation Board/Kit/Module (EVM) under the following conditions:

The user assumes all responsibility and liability for proper and safe handling of the goods. Further, the user indemnifies TI from all claims arising from the handling or use of the goods.

Should this evaluation board/kit not meet the specifications indicated in the User's Guide, the board/kit may be returned within 30 days from the date of delivery for a full refund. THE FOREGOING LIMITED WARRANTY IS THE EXCLUSIVE WARRANTY MADE BY SELLER TO BUYER AND IS IN LIEU OF ALL OTHER WARRANTIES, EXPRESSED, IMPLIED, OR STATUTORY, INCLUDING ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR ANY PARTICULAR PURPOSE. EXCEPT TO THE EXTENT OF THE INDEMNITY SET FORTH ABOVE, NEITHER PARTY SHALL BE LIABLE TO THE OTHER FOR ANY INDIRECT, SPECIAL, INCIDENTAL, OR CONSEQUENTIAL DAMAGES.

Please read the User's Guide and, specifically, the Warnings and Restrictions notice in the User's Guide prior to handling the product. This notice contains important safety information about temperatures and voltages. For additional information on TI's environmental and/or safety programs, please visit www.ti.com/esh or contact TI.

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REGULATORY COMPLIANCE INFORMATION

As noted in the EVM User's Guide and/or EVM itself, this EVM and/or accompanying hardware may or may not be subject to the Federal Communications Commission (FCC) and Industry Canada (IC) rules.

For EVMs **not** subject to the above rules, this evaluation board/kit/module is intended for use for ENGINEERING DEVELOPMENT, DEMONSTRATION OR EVALUATION PURPOSES ONLY and is not considered by TI to be a finished end product fit for general consumer use. It generates, uses, and can radiate radio frequency energy and has not been tested for compliance with the limits of computing devices pursuant to part 15 of FCC or ICES-003 rules, which are designed to provide reasonable protection against radio frequency interference. Operation of the equipment may cause interference with radio communications, in which case the user at his own expense will be required to take whatever measures may be required to correct this interference.

General Statement for EVMs including a radio

User Power/Frequency Use Obligations: This radio is intended for development/professional use only in legally allocated frequency and power limits. Any use of radio frequencies and/or power availability of this EVM and its development application(s) must comply with local laws governing radio spectrum allocation and power limits for this evaluation module. It is the user's sole responsibility to only operate this radio in legally acceptable frequency space and within legally mandated power limitations. Any exceptions to this are strictly prohibited and unauthorized by Texas Instruments unless user has obtained appropriate experimental/development licenses from local regulatory authorities, which is responsibility of user including its acceptable authorization.

For EVMs annotated as FCC – FEDERAL COMMUNICATIONS COMMISSION Part 15 Compliant

Caution

This device complies with part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) This device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

Changes or modifications not expressly approved by the party responsible for compliance could void the user's authority to operate the equipment.

FCC Interference Statement for Class A EVM devices

This equipment has been tested and found to comply with the limits for a Class A digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference when the equipment is operated in a commercial environment. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instruction manual, may cause harmful interference to radio communications. Operation of this equipment in a residential area is likely to cause harmful interference in which case the user will be required to correct the interference at his own expense.

FCC Interference Statement for Class B EVM devices

This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates, uses and can radiate radio frequency energy and, if not installed and used in accordance with the instructions, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, the user is encouraged to try to correct the interference by one or more of the following measures:

- Reorient or relocate the receiving antenna.
- Increase the separation between the equipment and receiver.
- Connect the equipment into an outlet on a circuit different from that to which the receiver is connected.
- Consult the dealer or an experienced radio/TV technician for help.

For EVMs annotated as IC – INDUSTRY CANADA Compliant

This Class A or B digital apparatus complies with Canadian ICES-003.

Changes or modifications not expressly approved by the party responsible for compliance could void the user's authority to operate the equipment.

Concerning EVMs including radio transmitters

This device complies with Industry Canada licence-exempt RSS standard(s). Operation is subject to the following two conditions: (1) this device may not cause interference, and (2) this device must accept any interference, including interference that may cause undesired operation of the device.

Concerning EVMs including detachable antennas

Under Industry Canada regulations, this radio transmitter may only operate using an antenna of a type and maximum (or lesser) gain approved for the transmitter by Industry Canada. To reduce potential radio interference to other users, the antenna type and its gain should be so chosen that the equivalent isotropically radiated power (e.i.r.p.) is not more than that necessary for successful communication.

This radio transmitter has been approved by Industry Canada to operate with the antenna types listed in the user guide with the maximum permissible gain and required antenna impedance for each antenna type indicated. Antenna types not included in this list, having a gain greater than the maximum gain indicated for that type, are strictly prohibited for use with this device.

Cet appareil numérique de la classe A ou B est conforme à la norme NMB-003 du Canada.

Les changements ou les modifications pas expressément approuvés par la partie responsable de la conformité ont pu vider l'autorité de l'utilisateur pour actionner l'équipement.

Concernant les EVMs avec appareils radio

Le présent appareil est conforme aux CNR d'Industrie Canada applicables aux appareils radio exempts de licence. L'exploitation est autorisée aux deux conditions suivantes : (1) l'appareil ne doit pas produire de brouillage, et (2) l'utilisateur de l'appareil doit accepter tout brouillage radioélectrique subi, même si le brouillage est susceptible d'en compromettre le fonctionnement.

Concernant les EVMs avec antennes détachables

Conformément à la réglementation d'Industrie Canada, le présent émetteur radio peut fonctionner avec une antenne d'un type et d'un gain maximal (ou inférieur) approuvé pour l'émetteur par Industrie Canada. Dans le but de réduire les risques de brouillage radioélectrique à l'intention des autres utilisateurs, il faut choisir le type d'antenne et son gain de sorte que la puissance isotrope rayonnée équivalente (p.i.r.e.) ne dépasse pas l'intensité nécessaire à l'établissement d'une communication satisfaisante.

Le présent émetteur radio a été approuvé par Industrie Canada pour fonctionner avec les types d'antenne énumérés dans le manuel d'usage et ayant un gain admissible maximal et l'impédance requise pour chaque type d'antenne. Les types d'antenne non inclus dans cette liste, ou dont le gain est supérieur au gain maximal indiqué, sont strictement interdits pour l'exploitation de l'émetteur.

【Important Notice for Users of this Product in Japan】

This development kit is NOT certified as Confirming to Technical Regulations of Radio Law of Japan

If you use this product in Japan, you are required by Radio Law of Japan to follow the instructions below with respect to this product:

1. Use this product in a shielded room or any other test facility as defined in the notification #173 issued by Ministry of Internal Affairs and Communications on March 28, 2006, based on Sub-section 1.1 of Article 6 of the Ministry's Rule for Enforcement of Radio Law of Japan,
2. Use this product only after you obtained the license of Test Radio Station as provided in Radio Law of Japan with respect to this product, or
3. Use of this product only after you obtained the Technical Regulations Conformity Certification as provided in Radio Law of Japan with respect to this product. Also, please do not transfer this product, unless you give the same notice above to the transferee. Please note that if you could not follow the instructions above, you will be subject to penalties of Radio Law of Japan.

Texas Instruments Japan Limited
(address) 24-1, Nishi-Shinjuku 6 chome, Shinjuku-ku, Tokyo, Japan

http://www.tij.co.jp

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日本テキサス· インスツルメンツ株式会社
東京都新宿区西新宿６丁目２４番１号
西新宿三井ビル
http://www.tij.co.jp

EVALUATION BOARD/KIT/MODULE (EVM) WARNINGS, RESTRICTIONS AND DISCLAIMERS

For Feasibility Evaluation Only, in Laboratory/Development Environments. Unless otherwise indicated, this EVM is not a finished electrical equipment and not intended for consumer use. It is intended solely for use for preliminary feasibility evaluation in laboratory/development environments by technically qualified electronics experts who are familiar with the dangers and application risks associated with handling electrical mechanical components, systems and subsystems. It should not be used as all or part of a finished end product.

Your Sole Responsibility and Risk. You acknowledge, represent and agree that:

1. You have unique knowledge concerning Federal, State and local regulatory requirements (including but not limited to Food and Drug Administration regulations, if applicable) which relate to your products and which relate to your use (and/or that of your employees, affiliates, contractors or designees) of the EVM for evaluation, testing and other purposes.
2. You have full and exclusive responsibility to assure the safety and compliance of your products with all such laws and other applicable regulatory requirements, and also to assure the safety of any activities to be conducted by you and/or your employees, affiliates, contractors or designees, using the EVM. Further, you are responsible to assure that any interfaces (electronic and/or mechanical) between the EVM and any human body are designed with suitable isolation and means to safely limit accessible leakage currents to minimize the risk of electrical shock hazard.
3. You will employ reasonable safeguards to ensure that your use of the EVM will not result in any property damage, injury or death, even if the EVM should fail to perform as described or expected.
4. You will take care of proper disposal and recycling of the EVM's electronic components and packing materials.

Certain Instructions. It is important to operate this EVM within TI's recommended specifications and environmental considerations per the user guidelines. Exceeding the specified EVM ratings (including but not limited to input and output voltage, current, power, and environmental ranges) may cause property damage, personal injury or death. If there are questions concerning these ratings please contact a TI field representative prior to connecting interface electronics including input power and intended loads. Any loads applied outside of the specified output range may result in unintended and/or inaccurate operation and/or possible permanent damage to the EVM and/or interface electronics. Please consult the EVM User's Guide prior to connecting any load to the EVM output. If there is uncertainty as to the load specification, please contact a TI field representative. During normal operation, some circuit components may have case temperatures greater than 60°C as long as the input and output are maintained at a normal ambient operating temperature. These components include but are not limited to linear regulators, switching transistors, pass transistors, and current sense resistors which can be identified using the EVM schematic located in the EVM User's Guide. When placing measurement probes near these devices during normal operation, please be aware that these devices may be very warm to the touch. As with all electronic evaluation tools, only qualified personnel knowledgeable in electronic measurement and diagnostics normally found in development environments should use these EVMs.

Agreement to Defend, Indemnify and Hold Harmless. You agree to defend, indemnify and hold TI, its licensors and their representatives harmless from and against any and all claims, damages, losses, expenses, costs and liabilities (collectively, "Claims") arising out of or in connection with any use of the EVM that is not in accordance with the terms of the agreement. This obligation shall apply whether Claims arise under law of tort or contract or any other legal theory, and even if the EVM fails to perform as described or expected.

Safety-Critical or Life-Critical Applications. If you intend to evaluate the components for possible use in safety critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, such as devices which are classified as FDA Class III or similar classification, then you must specifically notify TI of such intent and enter into a separate Assurance and Indemnity Agreement.

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