TI Designs

Indoor Light Energy Harvesting Reference Design for *Bluetooth®* Low Energy (BLE) Beacon Subsystem

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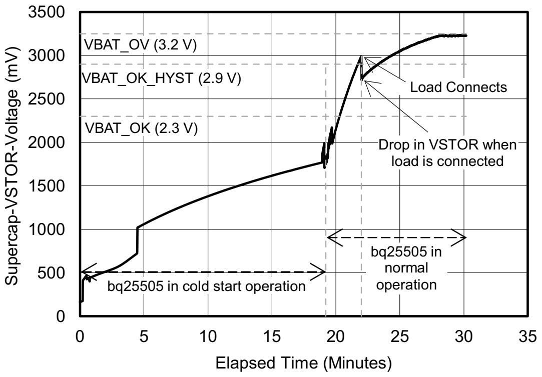
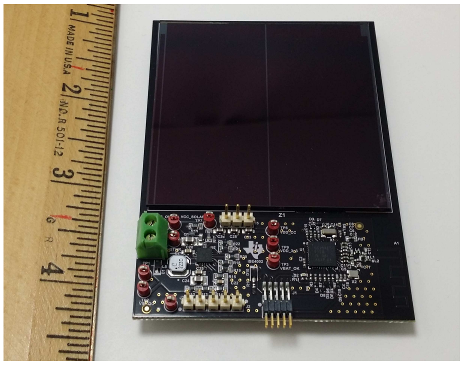
TI Designs provide the foundation that you need including methodology, testing and design files to quickly evaluate and customize the system. TI Designs help *you* accelerate your time to market.

Design Resources

TIDA-00100	Tool Folder Containing Design Files
bq25505	Product Folder
CSD75205W1015	Product Folder
CC2541	Product Folder

Supercap-VSTOR-Voltage (mV) at 450 LUX





Design Features

The Indoor Light Energy Harvesting Reference Design for *Bluetooth®* Low Energy (BLE) Beacon Subsystem works with no battery, re-charging, as well as works without any intervention in an indoor environment like retail stores or an office building.

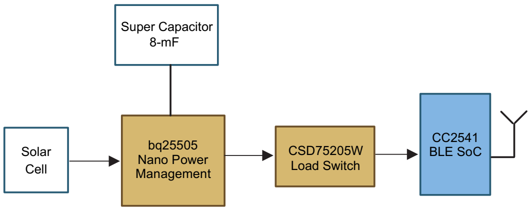
- *Bluetooth* Low Energy (BLE) Beacon Design that Uses Indoor Lighting as an Energy Source
- Ultra Low Power with High Efficiency DC/DC Boost Converter/Charger that Manages the Solar Cell
- Continuous Energy Harvesting from Low Input Sources: $V_{IN} \geq 100$ mV
- Ultra Low Quiescent Current: $I_Q < 330$-nA (Typical) of the Power Management IC and 1-µA of BLE Chip
- Cold-Start Voltage: $V_{IN} \geq 330$ mV (Typical) of the power management
- Programmable Dynamic Maximum Power Point Tracking (MPPT)
- Highly Integrated SoC for *Bluetooth* Low Energy
- No Battery, No Recharging, No Maintenance, No Limitation or Constraints Around Installation

Featured Applications

- Building Automation
- Smart Retail
- Smart Signage
- Proximity Marketing

TI E2E™ Community

ASK Our Analog Experts
WebBench® Calculator Tools



1 Key System Specifications

PARAMETER	SPECIFICATION			DETAILS
Solar Cell	Cymbet Solar Cell (amorphous type), works in indoor environment with fluorescent light			See Section 4.3
Working Environment	Indoor lighting (fluorescent light) greater than 250 LUX for this application			See Section 4.3, Section 8.1, and Section 8.2
Beacon Frequency	Default firmware will broadcast BLE beacon once each second			See Section 7
Solar Cell Size	2.3 inch x 2.3 inch, Amorphous Solar Cell			See Section 9.4
BLE Antenna	Meandered inverted F PCB antenna			See Section 5
V_BAT_OV	Threshold voltage to which Supercap gets charged		3.2 V	See Section 4.1.3
V_BAT_OK	Threshold voltage below which load (CC2541 BLE SoC) gets disconnected		2.3 V	See Section 4.1.4
V_BAT_OK_HYST	Threshold voltage above which load (CC2541 BLE SoC) gets connected		2.9 V	See Section 4.1.4
Visual Indicator	One heartbeat LED that blinks once in 2 seconds for 100 ms			See Section 7
System Control	Autonomous, no intervention required, the system gracefully comes up and starts broadcasting BLE beacons when the V_BAT_OK_HYST is above 2.9 V. The system gracefully disconnects the load, when theV_BAT_OK is less than 2.3 V.			See Section 8.7 and Section 8.8
Supercap Size	8-mF			See Section 4.4
Supercap Charge-Up Time (approximate)	450 LUX	Load Connect at 2.9 V from load disconnect at 1.8 V	2.7 minutes	See Section 8.4, and Section 8.5
	250 LUX	Load Connect at 2.9 V from load disconnect at 1.8 V	5.4 minutes	
	450 LUX	Load Connect at 2.9 V from a completely discharged Supercap (C29)	21 minutes	
	250 LUX	Load Connect at 2.9 V from a completely discharged Supercap (C29)	41 minutes	
Operating Conditions	Building indoor environment			

2 System Description

Indoor Light Energy Harvesting Reference Design for *Bluetooth* Low Energy (BLE) Beacon Subsystem provides a solution where by with just the power of the typical indoor lighting within retail environment (greater than 250 LUX) the *Bluetooth* Low Energy chip can broadcast *Bluetooth* Low Energy beacons.

This Subsystem reference design is highly differentiated over existing solutions as it incorporates no batteries, thus eliminating the hassle of battery replacement or battery charging, therefore saving tremendous costs associated with maintenance. This solution also ensures that there are no constraints around installation as long as there is a typical indoor lighting available. There is also no ON/OFF switch; the entire load connection and disconnection is handled by the power management IC; therefore ensuring that the solution is self managing.

Key System Design Requirements for this design were:

- Renewable Energy Source that is available in an indoor building environment (like a retail store or an office space).
- *Bluetooth* Low Energy chip that can be efficiently put into sleep mode when not transmitting the BLE beacon for power savings as well as meets the overall low power budget when transmitting the BLE beacon as dictated by the Renewable Energy Source.
- Power Management solution that is optimized to work with energy harvesting sources, supports low VIN, has extremely low quiescent currents (less than 0.5 uA), can handle the load connection and disconnection elegantly as well as manage the charging of an energy reservoir like a Supercap.
- Entire solution needs to be in a small form factor design, that can be easily installed.

Renewable Energy Source: Light as a renewable source of energy is always available in an operational office building or retail environment. A small form factor solar cell (~2.3 inch × 2.3 inch) from Cymbet CBC-PV-01N that can operate in indoor light environment was selected (see Section 4.3).

CC2541 BLE SOC from TI that has a sleep current of ~1 uA (internal timer running) as well as an efficient power profile during BLE transmission was selected (see Section 8.1).

bq25505: Ultra Low Power Boost Charger with Battery Management and Autonomous Power Multiplexor for Primary Battery in Energy Harvester Applications was selected. bq25505 has an extremely low VIN range with Cold-Start Voltage: $V_{IN} \geq 330$ mV as well as Ultra Low Quiescent Current of 325 nA. bq25505 also supports programmable MPPT for solar cell operation. **CSD75205W1015** device as a load switch controlled by bq25505 was selected as it provides an extremely low on resistance as well as gate charge.

CLG05P008F12–8 mF Supercap was used as an energy reservoir that can source the power requirements during the beacon transmission.

2.1 bq25505

The bq25505 is the first of a new family of intelligent integrated energy harvesting Nano-Power management solutions that are well suited for meeting the special needs of ultra low power applications. The product is specifically designed to efficiently acquire and manage the microwatts (µW) to miliwatts (mW) of power generated from a variety of DC sources like photovoltaic (solar) or thermal electric generators (TEGs). The bq25505 is a highly efficient boost charger targeted toward products and systems, such as wireless sensor networks (WSN) which have stringent power and operational demands. The design of the bq25505 starts with a DC-DC boost charger that requires only microwatts of power to begin operating.

Once started, the boost charger can effectively extract power from low voltage output harvesters such as TEGs or single or dual cell solar panels. The boost charger can be started with VIN as low as 330 mV, and once started, can continue to harvest energy down to V_{IN} = 100 mV.

The bq25505 implements a programmable maximum power point tracking (MPPT) sampling network to optimize the transfer of power into the device. Sampling of the VIN_DC open circuit voltage is programmed using external resistors, and that sample voltage is held with an external capacitor. For example, solar cells that operate at maximum power point (MPP) of 80% of their open circuit voltage, the resistor divider can be set to 80% of the VIN_DC voltage and the network will control the VIN_DC to operate near that sampled reference voltage. Alternatively, an external reference voltage can be provided by an MCU to produce a more complex MPPT algorithm.

The bq25505 was designed with the flexibility to support a variety of energy storage elements. The availability of the sources from which harvesters extract their energy can often be sporadic or time-varying. Systems will typically need some type of energy storage element, such as a re-chargeable battery, super capacitor, or conventional capacitor. The storage element will make certain constant power is available when needed for the systems. The storage element also allows the system to handle any peak currents that cannot directly come from the input source. To prevent damage to the storage element, both maximum and minimum voltages are monitored against the internally programmed undervoltage (UV) and user programmable overvoltage (OV) levels.

To further assist users in the strict management of their energy budgets, the bq25505 toggles the battery good flag to signal an attached microprocessor when the voltage on an energy storage battery or capacitor has dropped below a pre-set critical level. This should trigger the shedding of load currents to prevent the system from entering an undervoltage condition. The OV and battery good thresholds are programmed independently.

In addition to the boost charging front end, bq25505 provides the system with an autonomous power multiplexor gate drive. The gate drivers allow two storage elements to be multiplexed autonomously in order to provide a single power rail to the system load. This multiplexor is based off the VBAT_OK threshold which is resistor programmable by the user. This allows the user to set the level when the system is powered by the energy harvester storage element, for example, rechargable battery or super capacitor or a primary non-rechargeable battery (for example, two AA batteries). This type of hybrid system architecture allows for the run-time of a typical battery powered systems to be extended based on the amount of energy available from the harvester. If there is not sufficient energy to run the system due to extended "dark time," the primary battery is autonomously switched to the main system rail within 8 µsec in order to provide uninterrupted operation.

All the capabilities of bq25505 are packed into a small foot-print 20-lead 3,5-mm × 3,5-mm QFN package.

2.2 CC2541

The CC2541 is a power-optimized true system-on-chip (SoC) solution for both *Bluetooth* Low Energy and proprietary 2.4-GHz applications. It enables robust network nodes to be built with low total bill-of-material costs. The CC2541 combines the excellent performance of a leading RF transceiver with an industry-standard enhanced 8051 MCU, in-system programmable flash memory, 8-KB RAM, and many other powerful supporting features and peripherals. The CC2541 is highly suited for systems where ultra low power consumption is required. This is specified by various operating modes. Short transition times between operating modes further enable low power consumption.

The CC2541 is pin-compatible with the CC2540 in the 6-mm × 6-mm QFN40 package, if the USB is not used on the CC2540 and the I^{2}C/extra I/O is not used on the CC2541. Compared to the CC2540, the CC2541 provides lower RF current consumption. The CC2541 does not have the USB interface of the CC2540, and provides lower maximum output power in TX mode. The CC2541 also adds a HW I^{2}C interface.

2.3 CSD75205W1015

The device has been designed to deliver the lowest on resistance and gate charge in the smallest outline possible with excellent thermal characteristics in an ultra low profile. Low on resistance coupled with the small footprint and low profile make the device ideal for battery operated space constrained applications.

3 Block Diagram

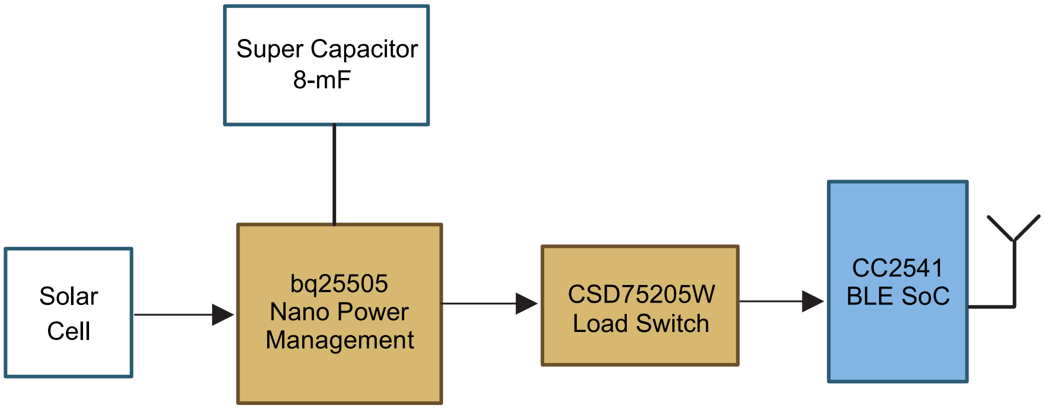


Figure 1. ***Bluetooth*** **Low Energy Beacon Subsystem Block Diagram**

3.1 Highlighted Products

Indoor Light Energy Harvesting Reference Design for *Bluetooth* Low Energy (BLE) Beacon Subsystem features the following devices:

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

- bq25505
  - Ultra Low Power Boost Charger with Battery Management and Autonomous Power Multiplexor for Primary Battery in Energy Harvester Applications
- CC2541
  - 2.4-GHz *Bluetooth* Low Energy and Proprietary System-on-Chip
- CSD75205W1015
  - P-Channel NexFET™ Power MOSFET

3.1.1 bq25505

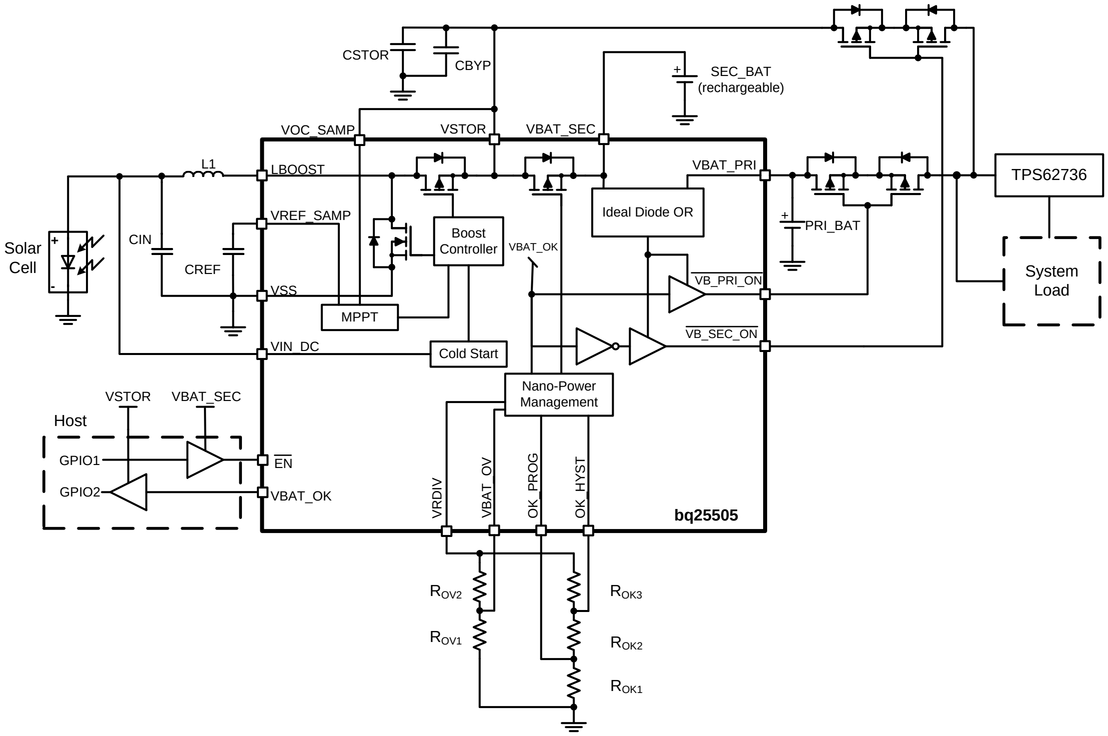


Figure 2. bq25505 Functional Block Diagram

- Ultra low power with high efficiency DC/DC boost charger
  - Cold-start voltage: $V_{IN} \geq 330$ mV
  - Continuous energy harvesting from input sources as low as 100 mV
  - Ultra low quiescent current of 325 nA
  - Input voltage regulation prevents collapsing high impedance input sources
  - Ship mode with < 5 nA from battery
- Energy storage
  - Energy can be stored to re-chargeable li-ion batteries, thin-film batteries, super-capacitors, or conventional capacitors
- Battery charging and protection
  - Internally set undervoltage level
  - User programmable overvoltage level
- Battery good output flag
  - Programmable threshold and hysteresis
  - Warn attached microcontrollers of pending loss of power
  - Can be used to enable/disable system loads
- Programmable Maximum Power Point Tracking (MPPT)
  - Integrated MPPT for optimal energy extraction from a variety of energy harvesters
- Gate drivers for primary (non-rechargeable) and secondary (rechargeable) storage element multiplexing
  - Autonomous switching based on VBAT_OK
  - Break-before-make prevents system rail droop

3.1.2 CC2541

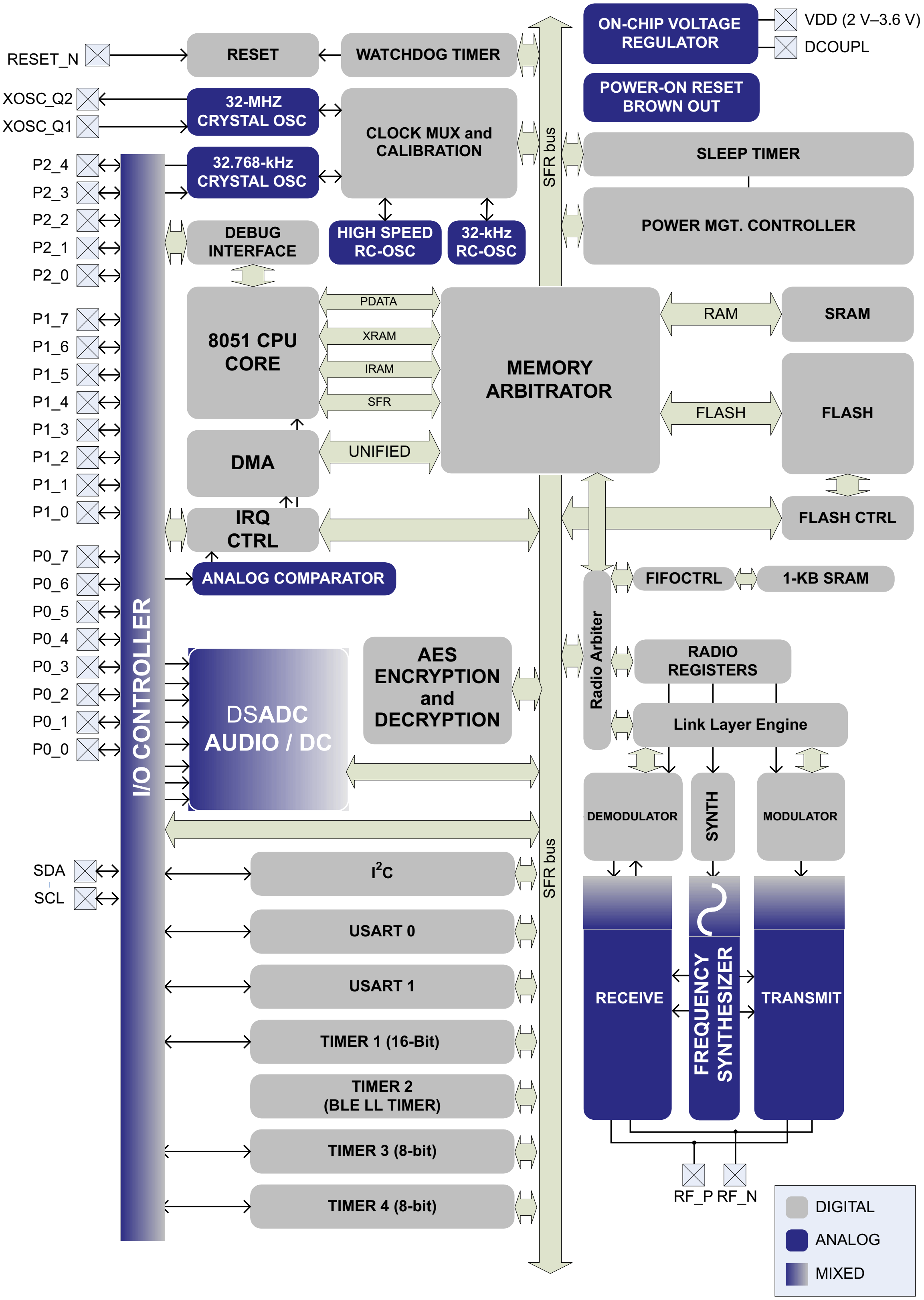


Figure 3. CC2541 Functional Block Diagram

- RF
  - 2.4-GHz *Bluetooth* Low Energy compliant and proprietary RF system-on-chip
  - 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^{2}C)
- 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)
- Microcontroller
  - High-performance and low-power 8051 microcontroller core with code pre-fetch
  - In-system-programmable flash, 128- or 256-KB
  - 8-KB RAM with retention in all power modes
  - Hardware debug support
  - Extensive baseband automation, including auto-acknowledgment and address decoding
  - Retention of all relevant registers in all power modes
- Peripherals
  - Powerful five-channel 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 USARTs with support for several serial protocols
  - 23 general-purpose I/O pins (21 × 4 mA, 2 × 20 mA)
  - I^{2}C interface
  - 2 I/O pins have led driving capabilities
  - Watchdog timer
  - Integrated high-performance comparator

3.1.3 CSD75205W1015

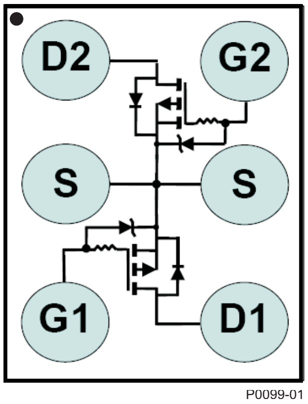


Figure 4. CSD75205W1015 Functional Block Diagram

- Dual P-Ch MOSFETs
- Common source configuration
- Small footprint 1,0-mm × 1,5-mm
- Gate-source voltage clamp
- Gate ESD protection –3 kV
- Pb free
- RoHS compliant
- Halogen free
- Applications
  - Battery management
  - Load switch
  - Battery protection

4 System Design Theory

4.1 Power Design Requirements for Solar and Low Power Wireless Sensor Node

Key challenges for Indoor Light Energy Harvesting Reference Design for *Bluetooth* Low Energy (BLE) Beacon Subsystem:

- The availability of the sources from which harvesters extract their energy can often be sporadic or time-varying. Thus energy harvesting systems will typically need some type of energy storage element, such as a re-chargeable battery, super capacitor, or conventional capacitor.
- Another challenge is peak current demands of wireless sensor node during a radio transmission. Thus, the storage element will make certain constant power is available when needed for the systems.
- It is important to remember that batteries and super capacitors can have significant leakage currents that need to be included with determining the loading on VSTOR.

The bq25505 is an integrated energy harvesting Nano-Power management solution that is well suited for meeting the special needs of ultra-low power applications. The product is specifically designed to efficiently acquire and manage the microwatts (μW) to milliwatts (mW) of power generated from a variety of high output impedance (Hi-Z) DC sources like photovoltaic (solar).

The bq25505 implements a highly efficient, pulse-frequency modulated (PFM) boost converter/charger targeted toward products and systems, such as wireless sensor networks (WSN) which have stringent power and operational demands. Assuming a depleted storage element has been attached, the bq25505 DC-DC boost converter/charger that requires only microwatts of power to begin operating in cold-start mode. Once the boost converter output, VSTOR, reaches ~1.8 V and can now power the converter, the main boost converter can now more efficiently extract power from low voltage output harvesters such as thermoelectric generators (TEGs) or single- and dual-cell solar panels. For example, assuming the Hi-Z input source can provide at least 5 μW typical and the load on VSTOR (including the storage element leakage current) is less than 1 μA of leakage current, the boost converter can be started with VIN_DC as low as 330 mV typical, and once VSTOR reaches 1.8 V, can continue to harvest energy down to VIN_DC ≈ 120 mV.

4.1.1 Maximum Output Power Point

Hi-Z DC sources have a maximum output power point (MPP) that varies with ambient conditions. For example, a solar panel's MPP varies with the amount of light on the panel and with temperature. The MPP is listed by the harvesting source manufacturer as a percentage of its open circuit (OC) voltage. Therefore, the bq25505 implements a programmable maximum power point tracking (MPPT) sampling network to optimize the transfer of power into the device. The bq25505 periodically samples the open circuit input voltage every 16 seconds by disabling the boost converter for 256 ms and stores the programmed MPP ratio of the OC voltage on the external reference capacitor (C22) at VREF_SAMP. Typically, solar cells are at their MPP when loaded to ~70–80% of their OC voltage. While the storage element is less than the user programmed maximum voltage (VBAT_OV), the boost converter loads the harvesting source until VIN_DC reaches the MPP (voltage at VREF_SAMP). This results in the boost charger regulating the input voltage of the converter until the output reaches VBAT_SEC_OV, thus transferring the maximum amount of power currently available per ambient conditions to the output.

4.1.2 Battery Undervoltage Protection

To prevent rechargeable batteries from being deeply discharged and damaged, and to prevent completely depleting charge from a capacitive storage element, the IC has an internally set undervoltage (VBAT_UV) threshold plus an internal hysteresis voltage (VBAT_UV_HYST). The VBAT_UV threshold voltage when the battery voltage is decreasing is internally set to 1.95 V (typical). The undervoltage threshold when battery voltage is increasing is given by VBAT_UV plus VBAT_UV_HYST. For most applications, the system load should be connected to the VSTOR pin while the storage element should be connected to the VBAT_SEC pin. Once the VSTOR pin voltage goes above the VBAT_UV_HYST threshold, the VSTOR pin and the VBAT_SEC pins are shorted. The switch remains closed until the VSTOR pin voltage falls below VBAT_UV. The VBAT_UV threshold should be considered a fail safe to the system; therefore the system load should be removed or reduced based on the VBAT_OK threshold which should be set above the VBAT_UV threshold.

The battery undervoltage, VBAT_UV, threshold is checked continuously to ensure that the internal battery FET, connecting VSTOR to VBAT_SEC, does not turn on until VSTOR is above the VBAT_UV threshold (2 V).The overvoltage (VBAT_OV) setting initially is lower than the programmed value at startup (varies on conditions) and is updated after the first ~32 ms. Subsequent updates are every ~64 ms. The VBAT_OV threshold sets maximum voltage on VSTOR and the boost converter stops switching when the voltage on VSTOR reaches the VBAT_OV threshold.

4.1.3 Battery Overvoltage Protection

To prevent rechargeable batteries from being exposed to excessive charging voltages and to prevent over charging a capacitive storage element, the over-voltage (VBAT_OV) threshold level must be set using external resistors. This is also the voltage value to which the charger will regulate the VSTOR/VBAT_SEC pin when the input has sufficient power. The VBAT_OV threshold when the battery voltage is rising is given by Equation 1:

$$\mathrm{VBAT\_OV} = \frac{3}{2}\mathrm{VBIAS}\left(1 + \frac{R_{OV2}}{R_{OV1}}\right) \tag{1}$$

The sum of the resistors is recommended to be no higher than 13 MΩ that is, R_{OV1} + R_{OV2} = 13 MΩ. The overvoltage threshold when battery voltage is decreasing is given by OV_HYST. It is internally set to the overvoltage threshold minus an internal hysteresis voltage denoted by VBAT_OV_HYST. Once the voltage at the battery exceeds VBAT_OV threshold, the boost charger is disabled. The charger starts again once the battery voltage falls below the VBAT_OV_HYST level.

4.1.4 Battery Voltage in Operating Range

The IC allows the user to set a programmable voltage independent of the overvoltage and undervoltage settings to indicate whether the VSTOR voltage (and therefore the VBAT_SEC voltage when the PFET between the two pins is turned on) is at an acceptable level. When the battery voltage is decreasing the threshold is set by Equation 2:

$$\mathrm{VBAT\_OK\_PROG} = \mathrm{VBIAS}\left(1 + \frac{R_{OK2}}{R_{OK1}}\right) \tag{2}$$

When the battery voltage is increasing, the threshold is set by Equation 3:

$$\mathrm{VBAT\_OK\_HYST} = \mathrm{VBIAS}\left(1 + \frac{R_{OK2} + R_{OK3}}{R_{OK1}}\right) \tag{3}$$

The sum of the resistors is recommended to be no higher than approximately that is, ROK1 + ROK2 + ROK3 = 13 MΩ. The logic high level of this signal is equal to the VSTOR voltage and the logic low level is ground. The logic high level has ~20 KΩ internally in series to limit the available current to prevent MCU damage until it is fully powered. The VBAT_OK_PROG threshold must be greater than or equal to the UV threshold.

4.1.5 Push Pull Drivers for Load Switches

There are two push-pull drivers intended to mulitplex between a primary non-rechargeable connected at VBAT_PRI and secondary storage element connected on VBAT_SEC based on the VBAT_OK signal. When the VBAT_OK signal goes high, indicating that the secondary rechargeable battery at VBAT_SEC is above the VBAT_OK_HYST threshold, the VB_PRI_ON output goes high followed by the VB_SEC_ON signal going low in order to connect VBAT_SEC to the system output (referred to as the VOR node). When VBAT_OK goes low, indicating that the secondary rechargeable battery at VBAT_SEC is below the VBAT_OK threshold, the VB_SEC_ON output goes high followed by the VB_PRI_ON signal going low in order to connect VBAT_PRI to the system. The drivers are designed to support up to 2 nF of gate capacitance and to drive a PMOS FET. The switching characteristics follow a break-before-make model, wherein during a transition, the drivers both go high for a typical dead time of 5 us before one of the signals goes low. The figure below shows the FET gate voltages for the transition from the secondary battery being connected to the system to the primary battery being connected.

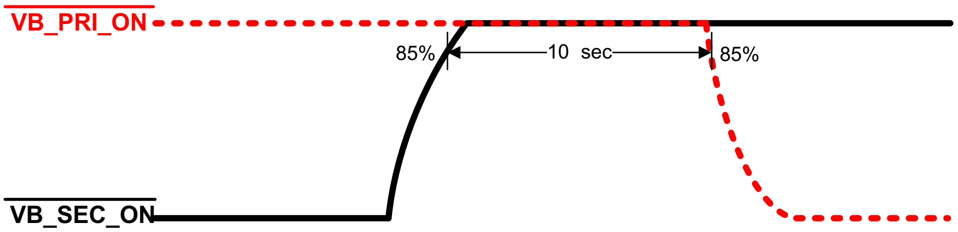


Figure 5. Break-Before-Make Operation of $\overline{\text{VB\_PRI\_ON}}$ and $\overline{\text{VB\_SEC\_ON}}$

4.1.6 Power Efficiency

$$\frac{P_{OUT}}{P_{IN}} = \frac{(V_{STOR} \times I_{STOR})}{(V_{IN} \times I_{IN})} = \eta \tag{4}$$

where η is the estimated efficiency for the same or similar configuration in order to determine the minimum input power needed to supply the desired output power. See the bq25505 User Guide.

4.2 LPRF Radio: Bluetooth Low Energy

First step with Low Power RF radio selection was to analyze the different possible wireless networking topologies and see what makes sense for a beacon application:

- Mesh: A message is sent from one point in a network to any other, by hopping through multiple slave nodes, for example Zigbee® or 6lowPAN technology.
- Star: A central host device communicates with a number of connected slave devices, for example, *Bluetooth* Low Energy connection between a PC and a mouse or keyboard.
- Broadcast: A message is sent from a device continuously and can be picked up by multiple devices.
- Scanning: A device that is constantly in receiving mode, waiting to pick up a signal within range.
- Point-to-Point: A one-to-one connection, where two device nodes can form a connection, for example, ANT+.

Table 1. Power Per Radio Technology

TECHNOLOGY	POWER PER BIT
ANT	0.71 uW/bit
Bluetooth Low Energy (BLE)	0.153 uW/bit
Zigbee	185 uW/bit
IrDA	11.7 uW/bit

In this design, it was required to establish communication between a radio beacon (slave node) and a smartphone (host). This would fall into either a star category or a broadcast category and thus between BLE and ANT as an option. BLE was selected for both power efficiency as well as the fact that both Apple® (iPhone 4S® and newer generations or an iPad 3® and newer generations) and Google™ (Android™ 4.3 onwards) support BLE stack in their software development kits as well as hardware.

As with classic *Bluetooth* technology, *Bluetooth* Low Energy technology operates in the 2.4 GHz ISM band and has similar radio frequency (RF) output power; however, since *Bluetooth* Low Energy device is in sleep mode most of the time and with the actual connection times of only a few milliseconds, the power consumption can be kept to a minimum.

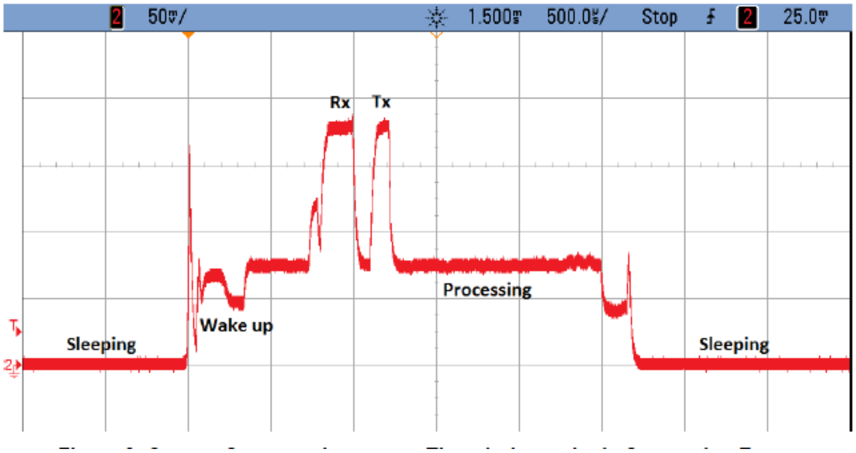


Figure 6. Current Consumption versus Time During a Single Connection Event

Many features like adaptive frequency hopping (AFH) as well as part of the logical link control and adaptation protocol (L2CAP) interface were inherited from classic *Bluetooth*. *Bluetooth* Low Energy technology also implements the same link security with simple pairing modes, secure authentication, and encryption. This inheritance makes *Bluetooth* Low Energy technology easy to set up, robust, and reliable in tough environments.

4.3 Solar Cell Description

The CBC-PV-01 photovoltaic cell used in this design is a low voltage amorphous silicon solar cell on a glass substrate (see CBC-PV-01 Photovoltaic Cell).

Typical operating voltage is 0.8 V with an output current of approximately 200 μA at 200 LUX in fluorescent light. The CBC-PV-01 is used in low power systems including wireless sensors and sensor networks.

4.4 Supercap Selection

In this design, Supercap is used to act as an energy reservoir for the transient load requirements associated with the *Bluetooth* Low Energy Beacon transmission (see Cellergy Supercapacitor) See Figure 6 to refer to the instantaneous power requirements during BLE beacon transmission.

Its important to ensure that the Supercap selected has a low ESR. As low ESR ensures that in applications requiring high power and short duration current pulses, voltage drop can be reduced. The decrease in voltage drop results better energy management. Supercaps store electrical charge electrostatically, and almost no reaction occurs between the electrodes and the electrolyte. Consequently, electrochemical capacitors can undergo hundreds of thousands of charge and discharge cycles which is important in an energy harvesting design as it ensures that there is no constraint around the life of the system tied to the Supercap charge-discharge cycling.

4.4.1 Energy Storage Element: Supercaps versus Re-Chargable Battery

The battery typically has little or no capacity below a certain voltage, whereas the capacitor does have capacity at lower voltages. A typical battery has a limitation on number of times it can be charged, whereas Supercaps can be recharged an order of magnitude more times than a battery. Both can have significant leakage currents that will appear as a DC load on VSTOR/VBAT_SEC. In this design the requirements were not to put any constraints around the battery charge and discharge cycles, thus Supercap was selected over a re-chargable battery solution.

5 *Bluetooth* Low Energy Antenna Simulations

Ansoft was used to simulate the hardware design file before fabrication to confirm the antenna performance.

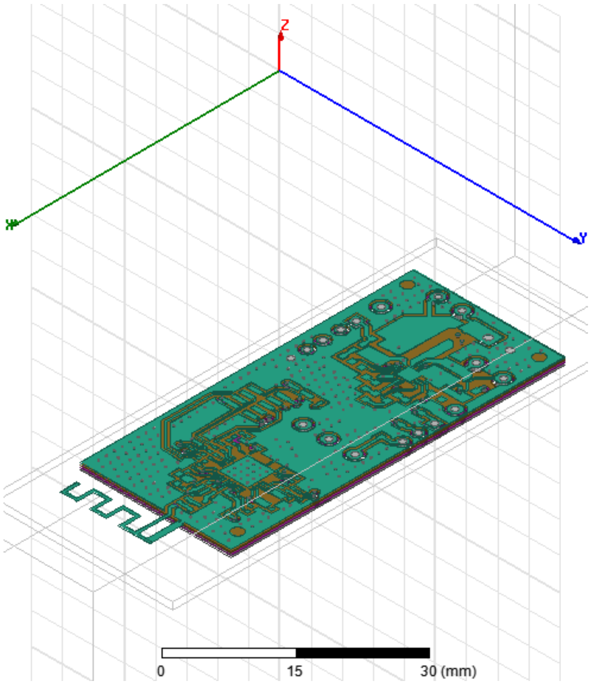


Figure 7. Simulation Setup

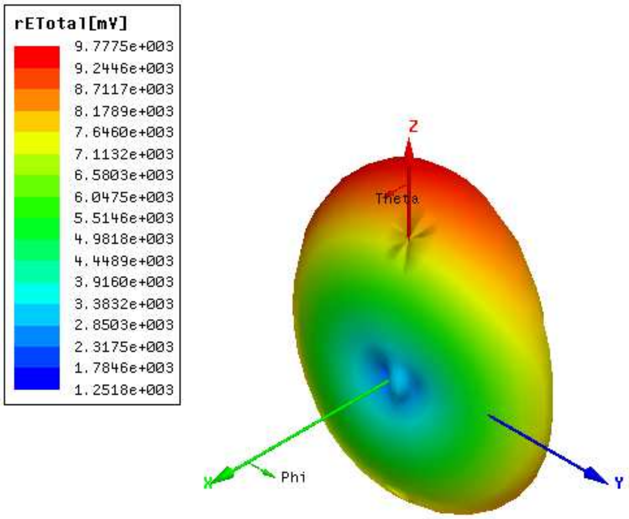


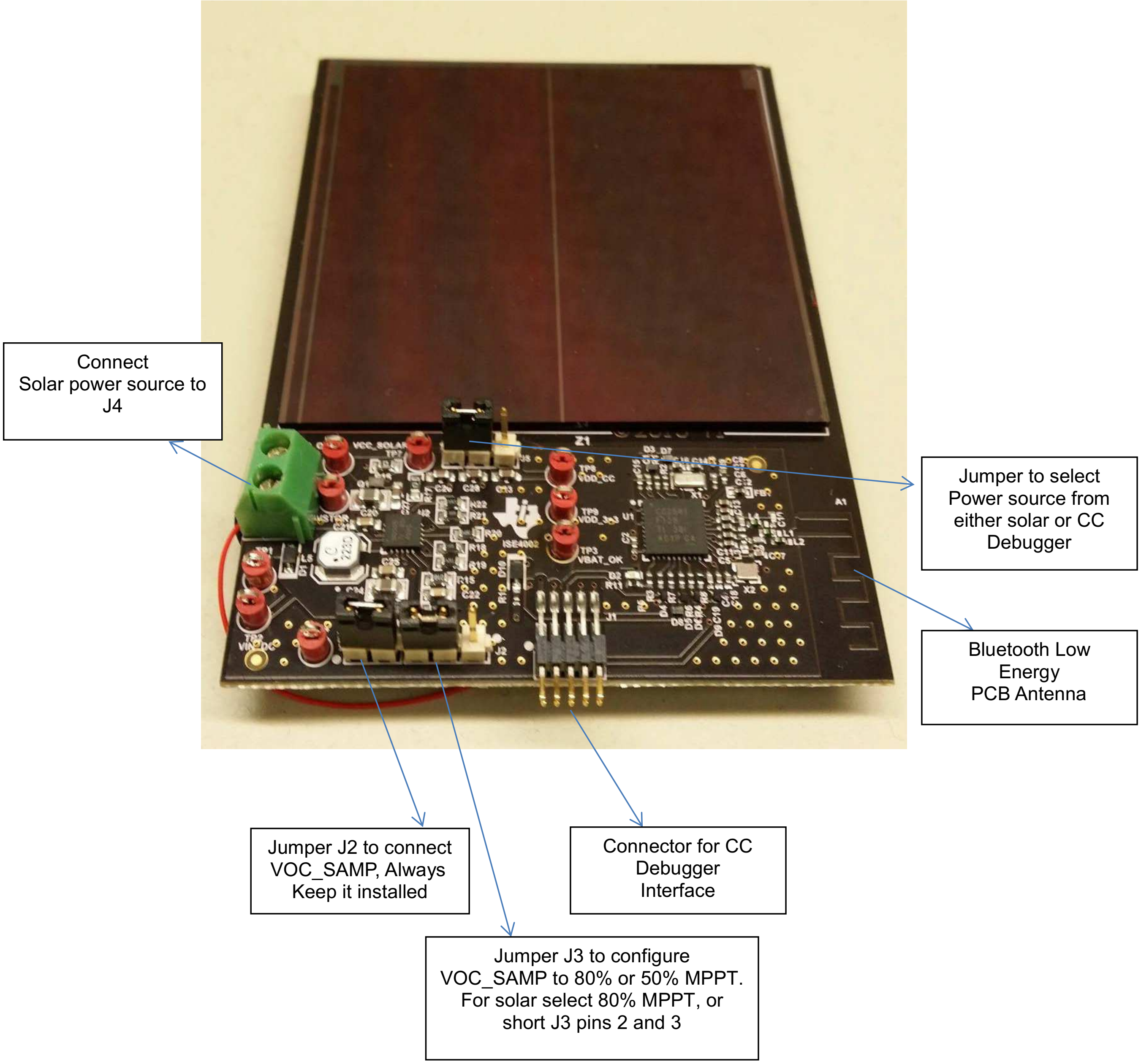
Figure 8. Antenna Simulations

Table 2. Antenna Simulations Results

QUANTITY	FREQUENCY	VALUE
MaxU	2.45 GHz	0.12679 W/sr
Peak Directivity		2.4637
Peak Gain		1.7563
Peak Realized Gain		1.5933
Radiated Power		0.64672 W
Accepted Power		0.90718 W
Incident Power		1 W
Radiation Efficiency		0.71289
Front to Back Ratio		N/A
Decay Factor		0

As shown in Table 2, antenna simulations confirmed that a meandered inverted F antenna would provide the required performance as needed for a broadcast BLE beacon functionality.

6 Getting Started Hardware



Connect Solar power source to J4

Jumper to select Power source from either solar or CC Debugger

Bluetooth Low Energy PCB Antenna

Jumper J2 to connect VOC_SAMP, Always Keep it installed

Connector for CC Debugger Interface

Jumper J3 to configure VOC_SAMP to 80% or 50% MPPT. For solar select 80% MPPT, or short J3 pins 2 and 3

Figure 9. Hardware Description

6.1 Functional Mode

- In Functional Mode, J5 pins 1 and 2 are shorted (see Figure 9), this ensures that the load (CC2541) is connected to the solar power source.
- In Functional mode or CC2541 programming mode, ensure that Jumper J2 is always installed and J3 pins 2 and 3 are shorted (see Figure 9), so that 80% MPPT is selected in case of solar energy harvesting.
- Connect the solar panel power leads to J4 (see Figure 9) interface which has screw terminal inputs.
- Monitor the voltage on TP5 (see Figure 26), as the solar panel charges the Supercap C29, the voltage on TP5 will increase and as soon as it reaches above 2.95 V, the load switch Q1 will connect the CC2541 load to the VSTOR pin of bq25505.
- There is no ON/OFF switch in this design. bq25505 manages the load connection by way of Q1. When the voltage on the VSTOR is above 2.95 V, CC2541 is connected to the VSTOR pins and when the voltage on the VSTOR falls below 2.36 V, CC2541 is disconnected from the VSTOR pin of bq25505. bq25505 controls the Q1 by way of the VB_SEC_ON pin (see Figure 26).
- To confirm the hardware is functioning ok, there is an LED – D2 visual indication that blinks once every 2 seconds for 100 ms.
- In functional mode, to confirm the *Bluetooth* Low Energy data is transmitted properly, SmartRF packet sniffer can be installed can be installed on a PC (see RF Packet Sniffer). For USB to BLE connectivity, a CC2540 based USB to BLE dongle needs to be connected to the PC USB port (see USB to BLE Dongle).
- Launch the SmartRF packet sniffer and hit start. A known packet as described in Figure 10 will be received.

P.nbr.	Time (us)	Channel	Access Address	Adv PDU Type	Adv PDU Header Type	TxAdd	RxAdd	PDU-Length	AdvA	AdvData	CRC	RSSI (dBm)	FCS
1	+0 =0	0x25	0x8E89BED6	ADV_NON_CONN_IND	2	0	0	13	0x84DD20EF199B	02 01 06 03 02 F0 FF	0xF0A3A7	-45	OK
2	+1008770 =1008770	0x25	0x8E89BED6	ADV_NON_CONN_IND	2	0	0	13	0x84DD20EF199B	02 01 06 03 02 F0 FF	0xF0A3A7	-45	OK
3	+1005020 =2013790	0x25	0x8E89BED6	ADV_NON_CONN_IND	2	0	0	13	0x84DD20EF199B	02 01 06 03 02 F0 FF	0xF0A3A7	-45	OK
4	+1000021 =3013811	0x25	0x8E89BED6	ADV_NON_CONN_IND	2	0	0	13	0x84DD20EF199B	02 01 06 03 02 F0 FF	0xF0A3A7	-45	OK
5	+1000645 =4014456	0x25	0x8E89BED6	ADV_NON_CONN_IND	2	0	0	13	0x84DD20EF199B	02 01 06 03 02 F0 FF	0xF0A3A7	-45	OK
6	+1003145 =5017601	0x25	0x8E89BED6	ADV_NON_CONN_IND	2	0	0	13	0x84DD20EF199B	02 01 06 03 02 F0 FF	0xF0A3A7	-45	OK
7	+1005020 =6022621	0x25	0x8E89BED6	ADV_NON_CONN_IND	2	0	0	13	0x84DD20EF199B	02 01 06 03 02 F0 FF	0xF0A3A7	-45	OK
8	+1000021 =7022642	0x25	0x8E89BED6	ADV_NON_CONN_IND	2	0	0	13	0x84DD20EF199B	02 01 06 03 02 F0 FF	0xF0A3A7	-45	OK
9	+1008770 =8031412	0x25	0x8E89BED6	ADV_NON_CONN_IND	2	0	0	13	0x84DD20EF199B	02 01 06 03 02 F0 FF	0xF0A3A7	-45	OK

Note: A known packet with AdvData **02 01 06 03 02 F0 FF** is received every ~1s.

This is the packet that The CC2541 on the solar energy harvesting board is programmed to transmit every ~1s.

Figure 10. Beacon Packet Description

6.2 Programming Mode

CC2541 Programming:

- CC Debugger (see CC Debugger) will be required to program the CC2541.
- Also Smart RF programmer software (see RF Flash Programmer) will be required to program the HEX file (see TIDA-00100) to the CC2541.
- To program the CC2541, ensure that J5 pins 2 and 3 (see Figure 9) are shorted by way of a jumper. This will ensure that the power to the system will be sourced from CC2541 and not solar while programming.
- Connect the CC Debugger to the Energy Harvesting Board as shown in Figure 11.

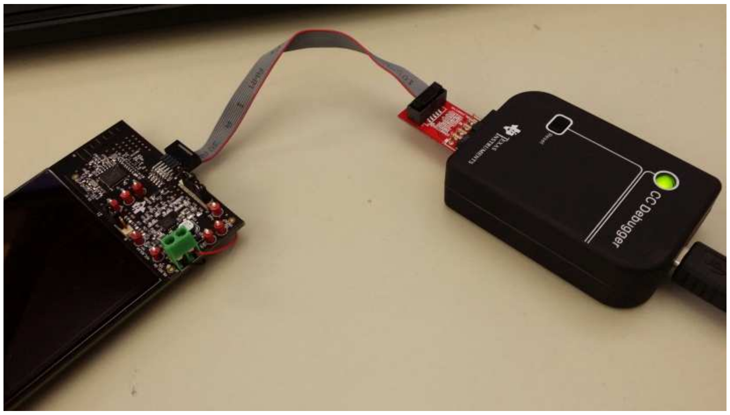


Figure 11. CC Debugger

- When the CC Debugger is connected properly, the Green LED will light up on the CC Debugger as shown in Figure 11.
- Launch the SMART RF Flash Programmer utility, and select the HEX file *Basic_Broadcaster_1s_LED_blink_CC2541DK-MINI-keyfob* (see TIDA-00100).
- Once installed, you will notice the LED will blink every 2 seconds for ~100 ms.

7 Getting Started Firmware

7.1 To modify the Firmware, IAR (see http://www.iar.com/) installation is required.

- Download and install the TI CC254x BLE-STACK v1.4.0 (available for download at BLE-STACK v1.4.0).
- Place the zip file “EnergyHarvestBroadvaster_BLEv1.4.0.zip” located at TIDA-00100 in the following directory (assuming that installation used the default path): C:\Texas Instruments\BLE-CC254x-1.4.0.
- Extract the zip file at that path. A message may pop up asking whether it is OK to overwrite existing files. Click ‘Yes’. You may want to make a copy of the existing files beforehand.
- Open up the following project in IAR 8.20: C:\Texas Instruments\BLE-CC254x-1.4.0\Projects\ble\SimpleBLEPeripheral\CC2541DB\SimpleBLEPeripheral.eww. Note that even though the project normally builds an application to run in the GAP Peripheral role, the modified source code will make it so the application only operates in a GAP Broacaster role.
- Build the project and download it to the CC2541.
- Run the application. Upon power-up, the CC2541 will automatically begin advertising with a 1s advertising interval, broadcasting non-connectable, non-scannable advertisements. The LED will blink for 100 ms once every 2 s.

7.2 Notes for modifying the application:

- To change the advertising interval, modify the defined value DEFAULT_ADVERTISING_INTERVAL in SimpleBLEPeripheral.c. The interval is specified in units of 0.625 ms (for example, value is 1600 for a 1 s advertising interval).
- To change the advertisement data, modify the array advertData.
- To change the LED on and off times, modify the defined values LED_BLINK_ON_TIME and LED_BLINK_OFF_TIME. These values are specified in units of 1 ms.

8 Test Data

8.1 Required Energy Budget Calculation and Data Collection:

Energy Budget for the BLE Beacon application is as follows:

- BLE Beacon transmitted once a second
- One heartbeat LED (visual indicator) that blinks once in 2 seconds for 100 ms (enough for visual confirmation that system is operational.
- Sleep current of CC2541 when it is not making the LED blink nor sending the BLE beacon.

As per the data sheet of CC2541, the sleep current of CC2541 (with internal timer still running) is 1 uA.

The LED (D2 selected) has a forward voltage drop of 2.1 V and with a limiting resistor (R11) of 2.2 kΩ, the current drawn by the LED when ON is:

$$\sim 1\text{ V} / 2200\ \Omega = 454\text{ uA} \quad (5)$$

To calculate the energy budget when the BLE packet is being transmitted, setup as shown in Figure 12 was used. In this setup, a 10 Ω resistor was connected in series with J5 pins 1 and 2. A voltage probe can then be attached differentially as shown in Figure 12. The oscilloscope can then capture the Voltage versus Time waveform which can be converted to Current versus Time by factoring into the 10 Ω series resistor.

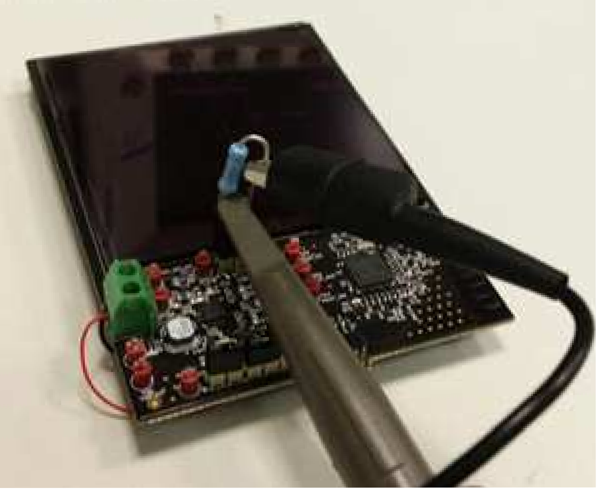


Figure 12. Current Probe Measurement for Dynamic Power Measurement

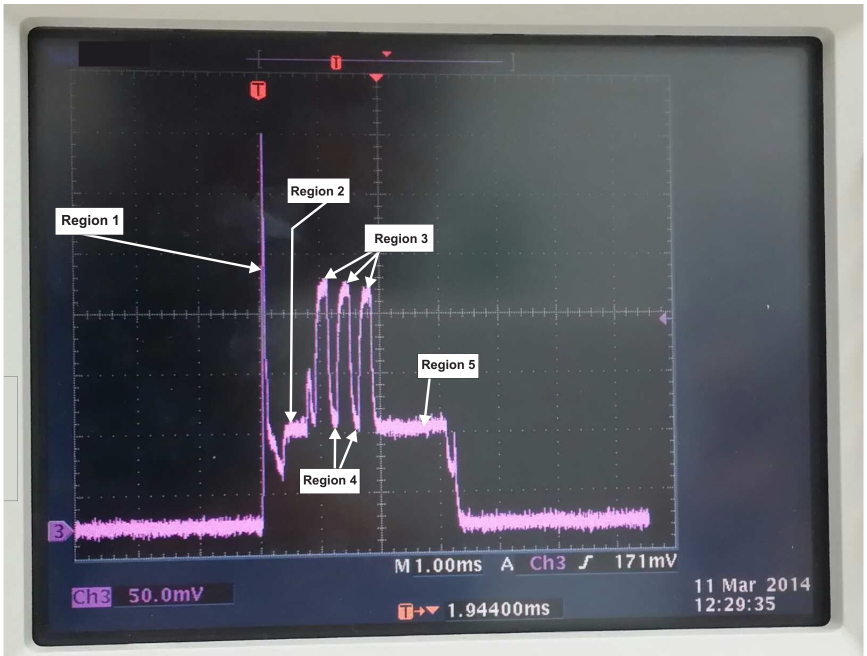


Figure 13. Power Drawn During Beacon Transmission

As shown in Figure 13, the current drawn by the CC2541 when transmitting a BLE beacon is captured. In summary, the total energy budget needed by the application is shown in Table 3:

Table 3. Energy (RMS) If Applicable

	CURRENT	VOLTAGE	POWER	TIME	ENERGY	ENERGY (RMS)
Event	mA	V	mA.V	ms	uW.s	uW.s
BLE Beacon Region 1	32	3.1	99.2	0.2	19.84[1]	14.03
BLE Beacon Region 2	7.5	3.1	23.25	0.6	13.95	13.95
BLE Beacon Region 3	7.5	3.1	23.25	0.4	9.30	9.30
BLE Beacon Region 4	20	3.1	62	0.6	37.20	37.20
BLE Beacon Region 5	7.5	3.1	23.25	1.4	32.55	32.55
LED Blinking	0.45	3.1	1.395	50	69.75	69.75
CC2541 Sleep	0.001	3.1	0.0031	946.8	2.94	2.94
		Total Energy Budget				**179.71 uW.s**

(1) Note that for the BLE Beacon Region 1, which is a high energy current pulse at the beginning, an RMS value has been used to realistically reflect the energy usage.

8.2 Energy Provided By the Solar Cell Under Different Light Conditions

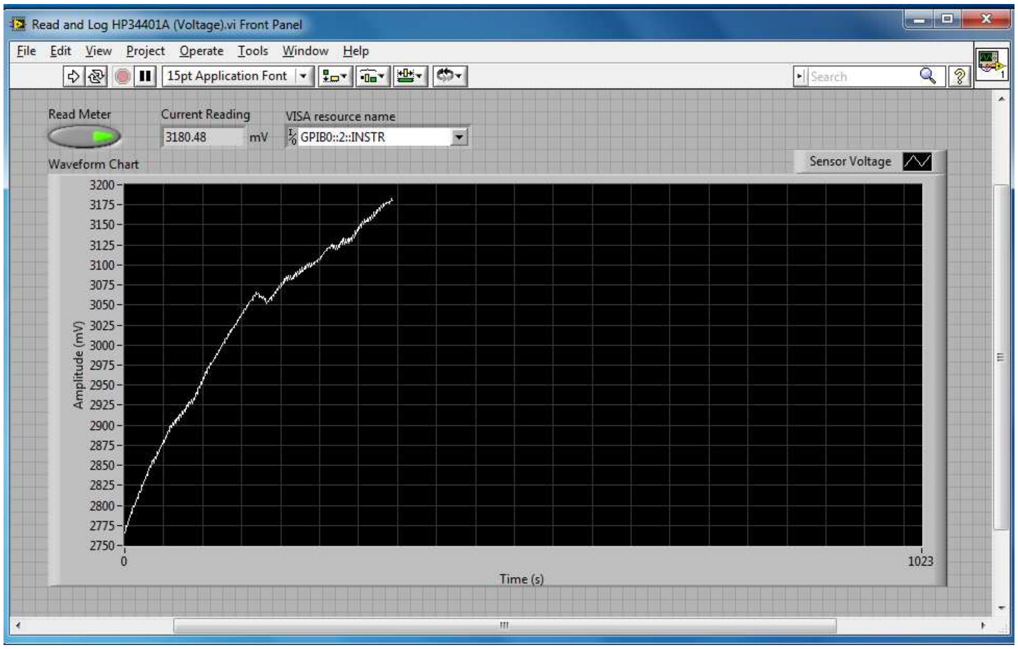
As shown in Section 8.1, the energy required by the CC2541 to transmit a BLE beacon once a second and blink an LED for 100 ms every 2 s, the energy budget required is ~179 uW.s. To confirm if the solar cell selected can support the required energy as well as to confirm the minimum lighting required to support the energy budget, below setup was used.

Figure 14. 450 LUX Light Intensity Measurement Setup

Figure 15. 250 LUX Light Intensity Measurement Setup

The system was kept in a typical lab environment. The light measured in the above setup in Figure 14 was ~450 LUX which is similar to a typical retail environment lighting. A multimeter was connected in series to J4 connector pin 2 such that the current going into the bq25505 can be measured. Also the voltage was measured after Schottky Diode D1 and Ground. The previously mentioned measurements were repeated for the 250 LUX setup (see Figure 15). Note that the system is placed under the shadow of the oscilloscope to cut down the light received.

8.3 LabView Software For Automated Measurements



Current Reading 3180.48 mV

VISA resource name GPIB0::2::INSTR

Figure 16. Labview Screen Shot

Labview Software was used to communicate to the hardware such that long time-constant data like Supercap charging can be collected effectively.

8.4 450 LUX Data Collection

Current Measured by Multimeter in Series between the Solar Cell and J4 connector pin 2: **350 uA**.

Voltage Measured after Schottky Diode D1 and Ground: toggles between **1.095 V and 1.383 V**.

Power Sourced by the Solar Cell under 450 LUX: between **383 uW and 484 uW**.

Assuming 85% efficiency of the bq25505 (see bq25505), the energy provided for the Supercap to get charged can be between: **325 uW.s and 411 uW.s**

Thus at 450 LUX, the energy provided by the solar cell is enough to charge the Supercap up to VBAT_OV (see Section 8.6).

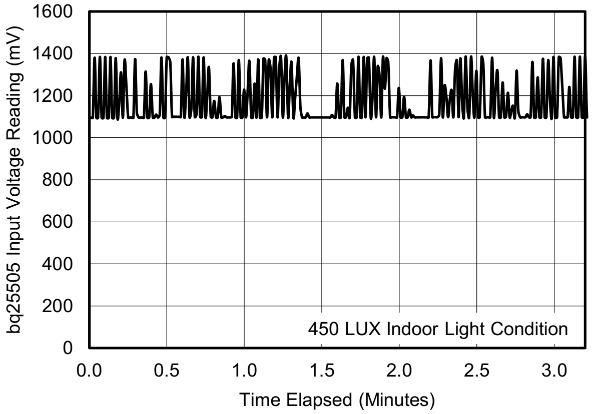


Figure 17. Input Voltage (450) LUX After Schottky Diode

bq25505 uses PFM switching, it regulated the input voltage instead of the output voltage. When the MPPT sampling circuit is active, VIN_DC = VPS = the harvester open circuit voltage (VIN_OC) because there is no input current to create a drop across the simulated impedance (that is, open circuit). When the boost converter is running, it draws only enough current until the voltage at VIN_DC droops to the MPPT's sampled voltage that is stored at VREF_SAMP. Thus as seen in Figure 17, the input voltage is regulated between the open circuit voltage of the solar cell and up to 80% MPPT's sampled voltage.

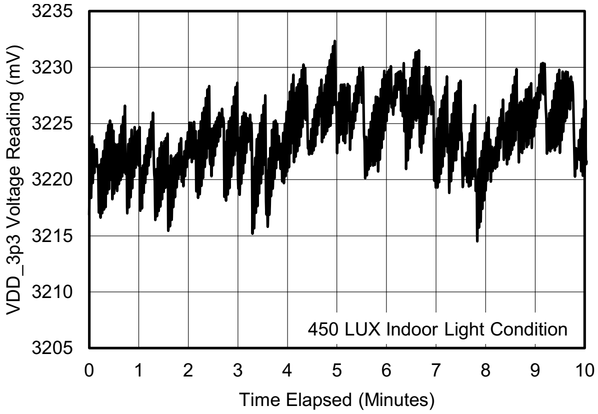


Figure 18. Voltage VDD_3p3 Measured During BLE Beacon Transmissions (Functional Mode)

As shown in Figure 18, in functional mode the VDD_3p3 voltage, which is the power provided to the load (CC2541) is approximately close to the VBAT_OV.

8.5 250 LUX Data Collection

Current Measured by Multimeter in Series between the Solar Cell and J4 connector pin 2: **195 uA**.

Voltage Measured after Schottky Diode D1 and Ground: relatively stable at **1.035 V**.

Power Sourced by the Solar Cell under 250 LUX: **~200 uW**.

Assuming 85% efficiency of the bq25505 (see bq25505) Energy that can be made available for the Supercap to charge is only: **170 uW** which is barely enough to keep up with the load requirements of the application (**~179 uW.s**) and thus leaving no energy left for the Supercap to get charged to VBAT_OV (see Section 8.7).

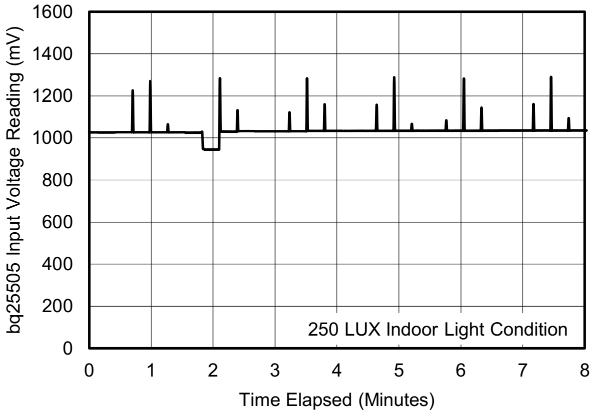


Figure 19. Input Voltage (250) LUX After Schottky Diode

As there is not enough energy to charge the Supercap to the VBAT_OV value, the bq25505 stays in the boost mode for most of the time.

8.6 Supercap Charging Under 450 LUX

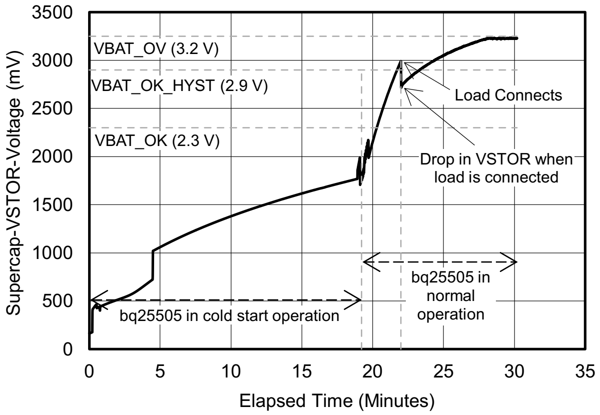


Figure 20. Supercap Charging Under 450 LUX

As shown in Figure 20, until 1.8 V, the bq25505 operates in the cold start mode, under 450 LUX condition, it takes ~20 minutes to charge the Supercap from no charge to 1.8 V. After the 1.8 V threshold, the bq25505 enters into normal boost charge operation and takes approximately ~2.7 minutes to charge up to the V_BAT_OK_HYST level of 2.9 V when the load gets connected and BLE beacon application starts. As noted in Figure 20, under 450 LUX, there is enough energy sourced by the solar cell to charge the Supercap up to the VBAT_OV value of ~3.2 V.

8.7 Supercap Charging Under 250 LUX

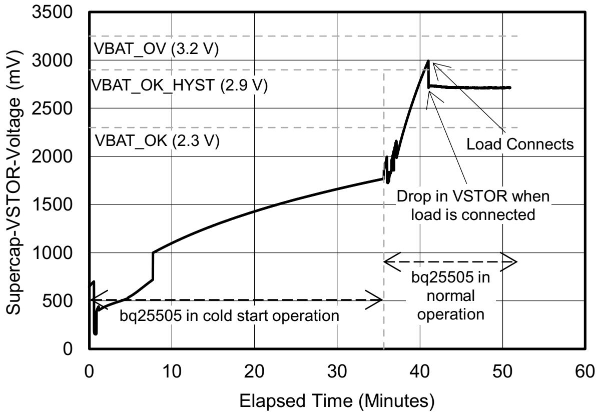


Figure 21. Supercap Charging Under 250 LUX

As shown in Figure 21, until 1.8 V, the bq25505 operates in the cold start mode, under 250 LUX condition, it takes ~35 minutes to charge the Supercap from no charge to 1.8 V. After the 1.8 V threshold, the bq25505 enters into normal boost charge operation and takes approximately ~5.4 minutes to charge up to the V_BAT_OK_HYST level of 2.9 V when the load gets connected and BLE beacon application starts. As noted in Figure 21, under 250 LUX, there is NOT enough energy sourced by the solar cell to charge the Supercap up to the VBAT_OV value of ~3.2 V. The voltage on Supercap remains steady and, as seen in Section 8.2, it is barely enough to sustain the energy requirements of the load.

8.8 Load Connect and Disconnect

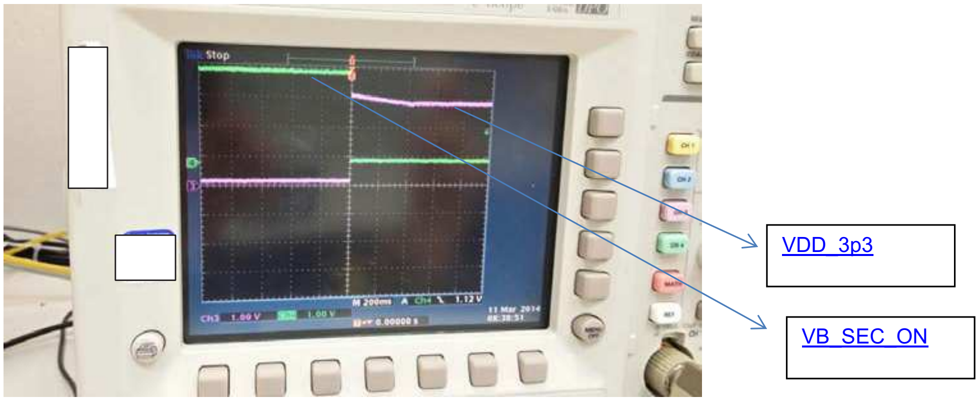


Figure 22. Load Connect

Load (CC2541) is connected to the bq25505 by way of the load switch Q1 as shown in Figure 26.

VB_SEC_ON as shown in Figure 22, is the control signal managed by bq25505 to turn ON/OFF the load switch Q1.

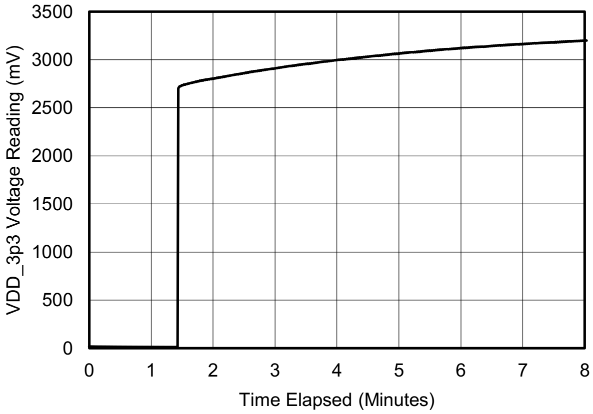


Figure 23. VDD_3p3 After Load Switch as Controlled by bq25505

As shown in Figure 23, it took ~1.3 minutes from the time when the load was disconnected to the time it was connected back or basically to charge the cap from VBAT_OK to VBAT_OK_HYST.

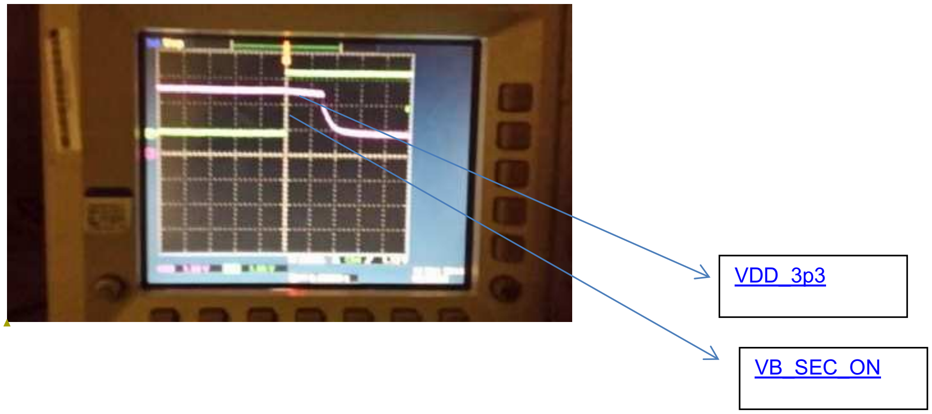


Figure 24. Load Disconnect

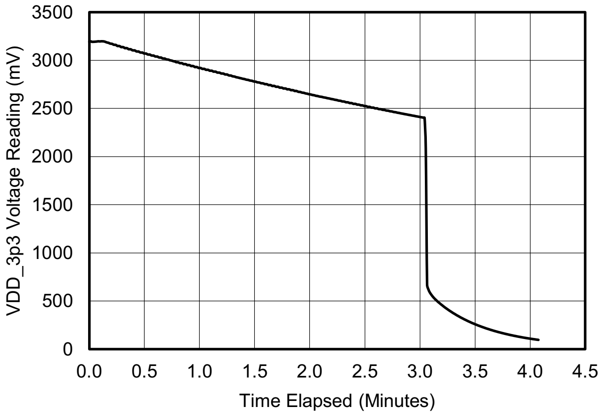


Figure 25. VDD_3p3 After Load Switch as Controlled by bq25505

As shown in Figure 25, it took ~3 minutes from the time when light source was removed to the time when the load was disconnected, basically the time for the voltage on the Supercap to go from ~VBAT_OV to VBAT_OK threshold.

9 Design Files

9.1 Schematics

The schematics are presented in the following order:

1. Energy Harvesting Beacon Schematic (see Figure 26)
2. CC2541 *Bluetooth* Low Energy SoC Schematic (see Figure 27)

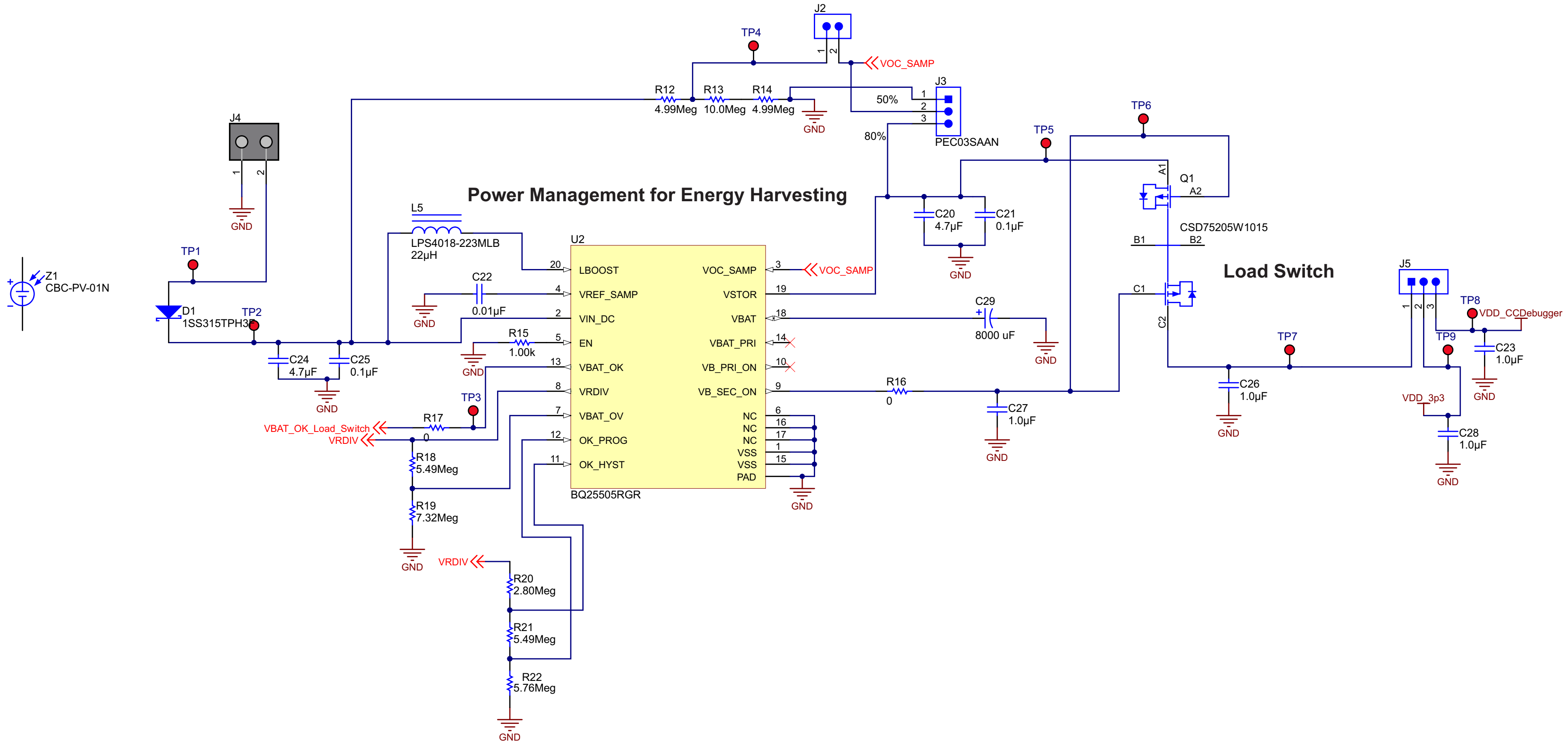


Figure 26. Energy Harvesting Beacon Schematic

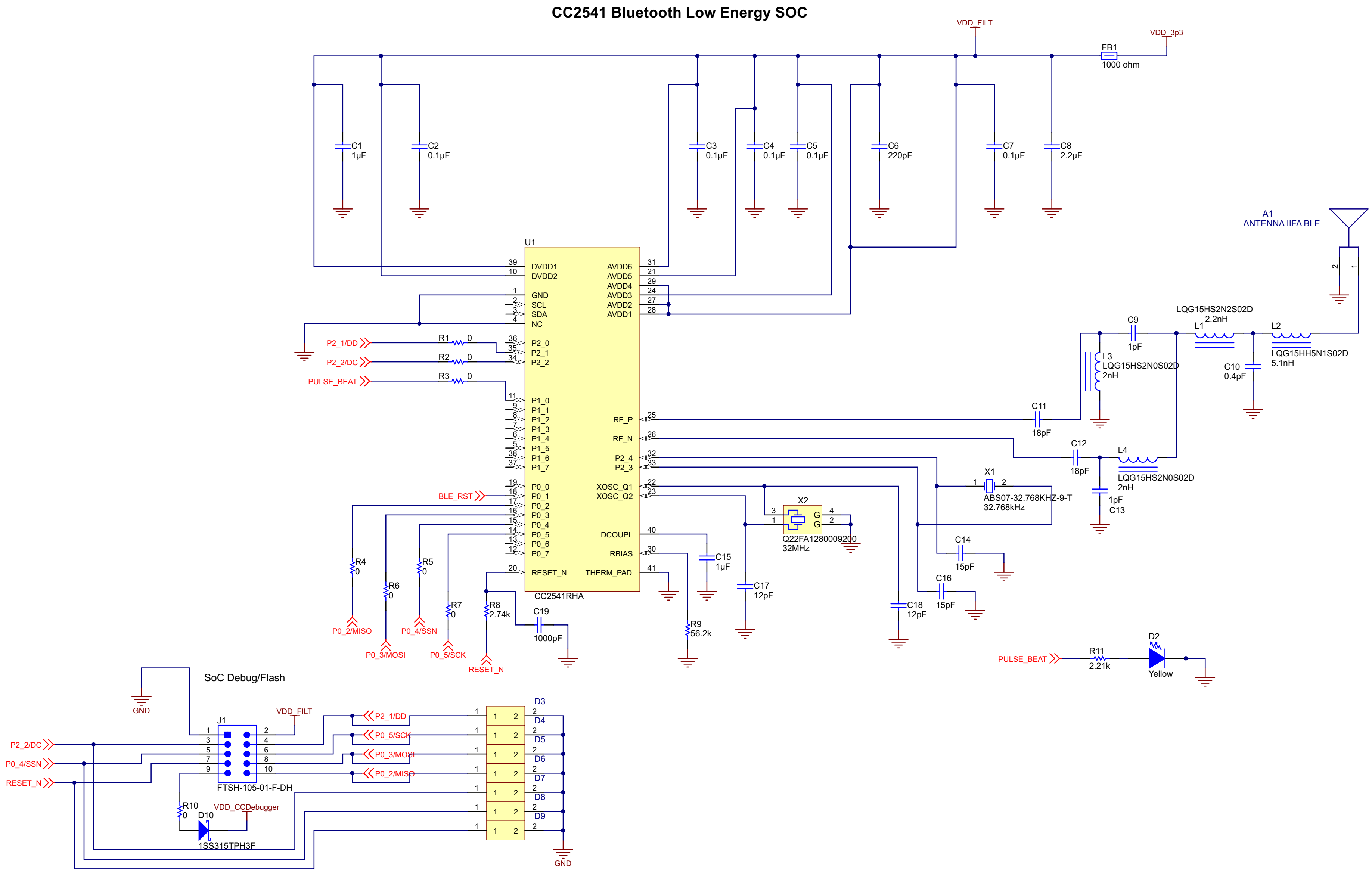


Figure 27. CC2541 *Bluetooth* Low Energy SOC Schematic

9.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00100. Table 4 shows the BOM for the Energy Harvesting Beacon.

Table 4. BOM

DESIGNATOR	DESCRIPTION	MANUFACTURER	PART NUMBER	QUANTITY
!PCB1	Printed Circuit Board	Any	ISE4002	1
C1, C15	CAP, CERM, 1 uF, 6.3 V, ±20%, X5R, 0402	TDK	C1005X5R0J105M	2
C2, C3, C4, C5, C7	CAP, CERM, 0.1 uF, 10 V, ±10%, X7R, 0402	MuRata	GRM155R71A104KA01D	5
C6	CAP, CERM, 220 pF, 50 V, ±5%, C0G/NP0, 0402	MuRata	GRM1555C1H221JA01D	1
C8	CAP, CERM, 2.2 uF, 6.3 V, ±20%, X5R, 0402	Taiyo Yuden	JMK105BJ225MV-F	1
C9, C13	CAP, CERM, 1 pF, 50 V, ±5%, C0G/NP0, 0402	MuRata	GRM1555C1H1R0CA01D	2
C10	CAP, CERM, 0.4 pF, 50 V, ±25%, C0G/NP0, 0402	MuRata	GRM1555C1HR40BA01D	1
C11, C12	CAP, CERM, 18 pF, 50 V, ±5%, C0G/NP0, 0402	MuRata	GRM1555C1H180JA01D	2
C14, C16	CAP, CERM, 15 pF, 50 V, ±5%, C0G/NP0, 0402	MuRata	GRM1555C1H150JA01D	2
C17, C18	CAP, CERM, 12 pF, 50 V, ±5%, C0G/NP0, 0402	MuRata	GRM1555C1H120JA01D	2
C19	CAP, CERM, 1000 pF, 50 V, ±5%, C0G/NP0, 0402	MuRata	GRM1555C1H102JA01D	1
C20, C24	CAP, CERM, 4.7 uF, 10 V, ±10%, X5R, 0805	Kemet	C0805C475K8PACTU	2
C21, C25	CAP, CER, 0.1 uF, 6.3 V, 10%, X5R, 0603	AVX Corporation	06036D104KAT2A	2
C22	CAP, CERM, 0.01 uF, 50 V, ±10%, X7R, 0603	MuRata	GRM188R71H103KA01D	1
C23, C26, C27, C28	CAP, CER, 1 uF, 10 V, 20%, X5R, 0603	Murata Electronics North America	GRM188R61A105MA61D	4
C29	Supercapacitors / Ultracapacitors 5.5 V, 8 uF FLAT LEADS	Cellergy	CLG05P008F12	1
D1, D10	Diode, Schottky, 5 V, 0.03 A, SOD-323	Toshiba	1SS315TPH3F	2
D2	LED, Yellow, SMD	Rohm	SML-P12YTT86	1
D3, D4, D5, D6, D7, D8, D9	ESD in 0402 Package with 10 pF Capacitance and 6 V Breakdown, 1 Channel, –40 to +125°C, 2-pin X2SON (DPY), Green (RoHS & no Sb/Br)	Texas Instruments	TPD1E10B06DPYR	7
FB1	0.25 A Ferrite Bead, 1000 Ω @ 100 MHz, SMD	MuRata	BLM15HG102SN1D	1
FID1, FID2, FID3	Fiducial mark. There is nothing to buy or mount.	N/A	N/A	3
H1, H2, H3, H4	Screw, Pan Head , 4-40, 3/8", Nylon	B&F Fastener Supply	NY PMS 440 0038 PH	4
H5, H6, H7, H8	Nut, Hex, 4-40, Nylon	B&F Fastener Supply	NY HN 440	4
H9, H10, H11, H12	Bumpon, Hemisphere, 0.44 × 0.20, Clear	3M	SJ-5303 (CLEAR)	4
J1	Header, 50 mil, 5 x 2, R/A, SMT	Samtec	FTSH-105-01-F-DH	1
J2	Header, 100 mil, 2 x 1, Tin plated, TH	Sullins Connector Solutions	PEC02SAAN	1
J3, J5	Header, 100 mil, 3 x 1, Tin plated, TH	Sullins Connector Solutions	PEC03SAAN	2
J4	TERMINAL BLOCK 3.5 MM 2POS PCB	On Shore Technology Inc	ED555/2DS	1
L1	Inductor, Multilayer, Air Core, 2.2 nH, 0.3 A, 0.12 Ω, SMD	MuRata	LQG15HS2N2S02D	1
L2	Inductor, Multilayer, Air Core, 5.1 nH, 0.3 A, 0.2 Ω, SMD	MuRata	LQG15HH5N1S02D	1
L3, L4	Inductor, Multilayer, Air Core, 2 nH, 0.3 A, 0.1 Ω, SMD	MuRata	LQG15HS2N0S02D	2
L5	Inductor, Shielded Drum Core, Ferrite, 22 uH, 0.83 A, 0.36 Ω, SMD	Coilcraft	LPS4018-223MLB	1
LBL1	Thermal Transfer Printable Labels, 0.650" W x 0.200" H - 10,000 per roll	Brady	THT-14-423-10	1
Q1	P-Channel NexFET^{TM} Power MOSFET, YZC0006ABBB	Texas Instruments	CSD75205W1015	1
R1, R2, R3, R4, R5, R6, R7, R10	RES, 0 Ω, 5%, 0.063 W, 0402	Vishay-Dale	CRCW04020000Z0ED	8
R8	RES, 2.74 k Ω, 1%, 0.063 W, 0402	Vishay-Dale	CRCW04022K74FKED	1
R9	RES, 56.2 k Ω, 1%, 0.063 W, 0402	Vishay-Dale	CRCW040256K2FKED	1
R11	RES, 2.21 k Ω, 1%, 0.063 W, 0402	Vishay-Dale	CRCW04022K21FKED	1
R12, R14	RES, 4.99 Meg Ω, 1%, 0.1 W, 0603	Vishay-Dale	CRCW06034M99FKEA	2
R13	RES, 10.0 Meg Ω, 1%, 0.1 W, 0603	Vishay-Dale	CRCW060310M0FKEA	1
R15	RES, 1.00 k Ω, 1%, 0.1 W, 0603	Vishay-Dale	CRCW06031K00FKEA	1
R16, R17	RES, 0 Ω, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06030000Z0EA	2
R18, R21	RES, 5.49 Meg Ω, 1%, 0.1 W, 0603	Vishay-Dale	CRCW06035M49FKEA	2
R19	RES, 7.32 Meg Ω, 1%, 0.1 W, 0603	Vishay-Dale	CRCW06037M32FKEA	1

Table 4. BOM (continued)

DESIGNATOR	DESCRIPTION	MANUFACTURER	PART NUMBER	QUANTITY
R20	RES, 2.80 Meg Ω, 1%, 0.1 W, 0603	Vishay-Dale	CRCW06032M80FKEA	1
R22	RES, 5.76 Meg Ω, 1%, 0.1 W, 0603	Vishay-Dale	CRCW06035M76FKEA	1
TP1, TP2, TP3, TP4, TP5, TP6, TP7, TP8, TP9	Test Point, Miniature, Red, TH	Keystone	5000	9
U1	2.4-GHz *Bluetooth* Low Energy and Proprietary System-on-Chip, RHA0040H	Texas Instruments	CC2541RHA	1
U2	Ultra Low Power Boost Converter with Battery Management for Energy Harvester Applications, RGR0020A	Texas Instruments	bq25505RGR	1
X1	CRYSTAL, 32.768 KHZ, 9 pF, SMD	Abracon Corportation	ABS07-32.768KHZ-9-T	1
X2	Crystal, 32 MHz, 10 pF, SMD	Epson	Q22FA1280009200	1
Z1	PHOTOVOLTAIC SOLAR CELL	Cymbet Corporation	CBC-PV-01N	1

9.3 Layer Plots

To download the layer plots, see the design files at TIDA-00100. Figure 28, Figure 29, Figure 30, Figure 31, Figure 32, Figure 33, Figure 34, Figure 35, Figure 36 and Figure 37 show the layer plots for the Energy Harvesting Beacon respectively.

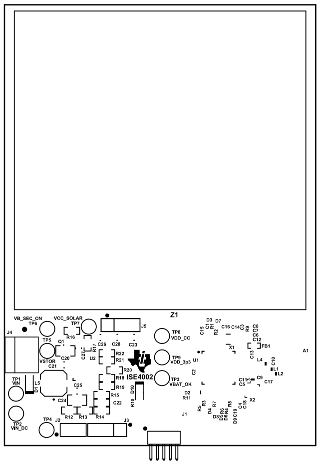


Figure 28.

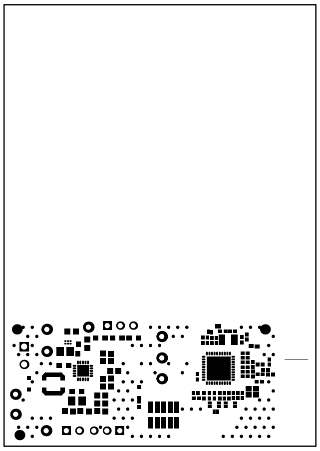


Figure 29.

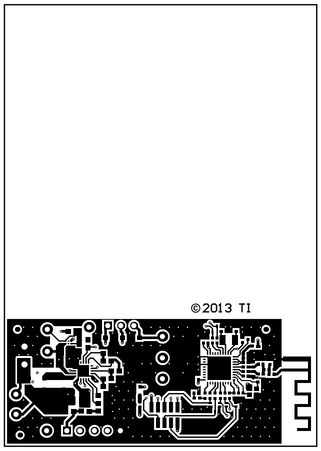


Figure 30.

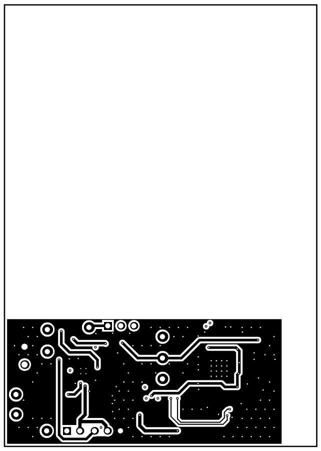


Figure 31.

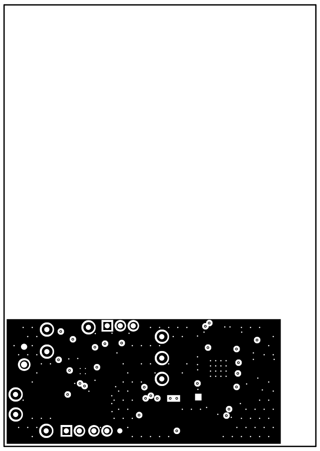


Figure 32.

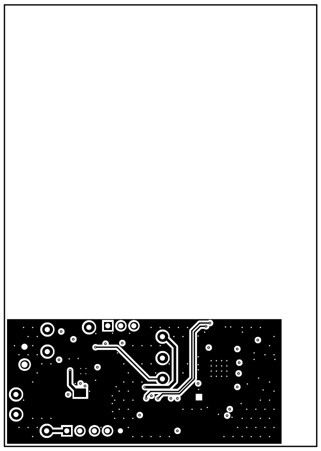


Figure 33.

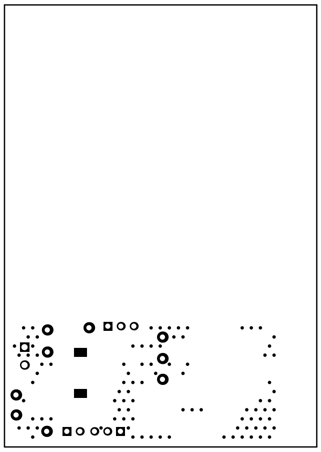


Figure 34.

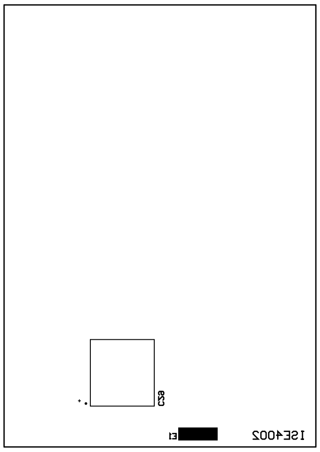


Figure 35.

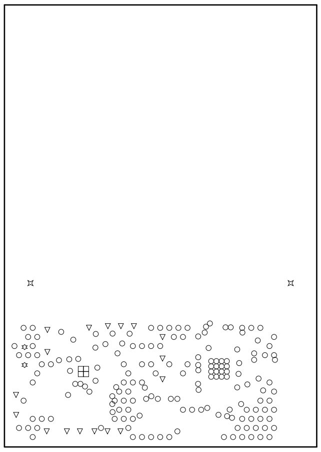


Figure 36.

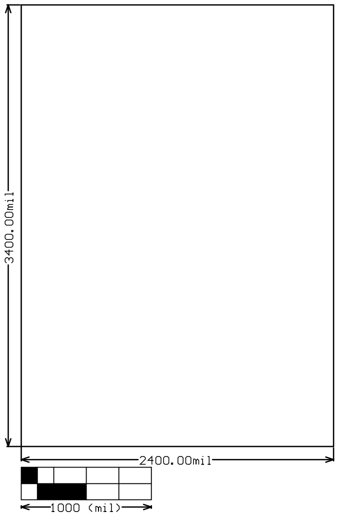


Figure 37.

9.4 Altium Project

To download the Altium project files, see the design files at TIDA-00100. Figure 38, Figure 39, Figure 40, Figure 41, and Figure 42 show the layout for the Energy Harvesting Beacon respectively.

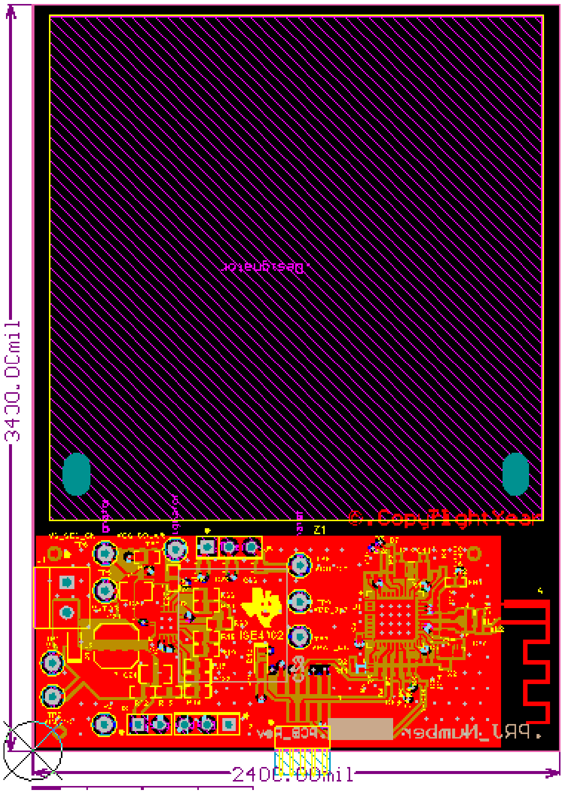


Figure 38. All Layers

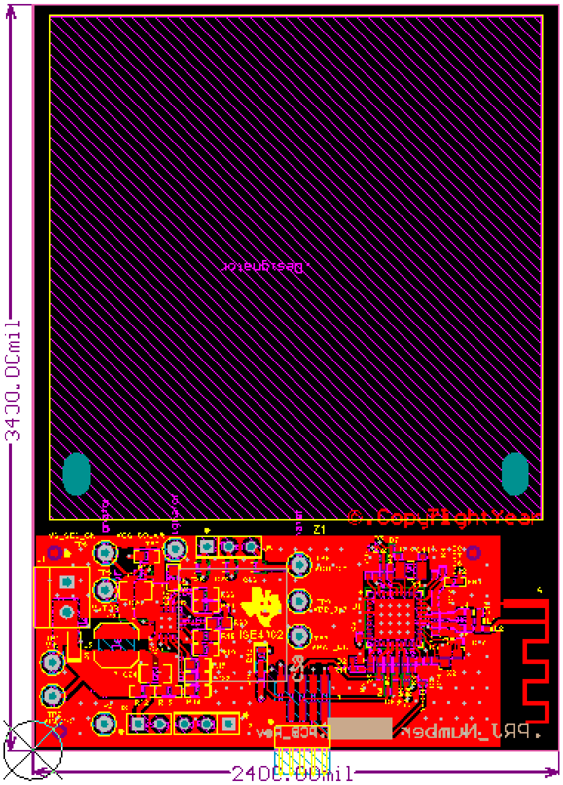


Figure 39. Top Layer

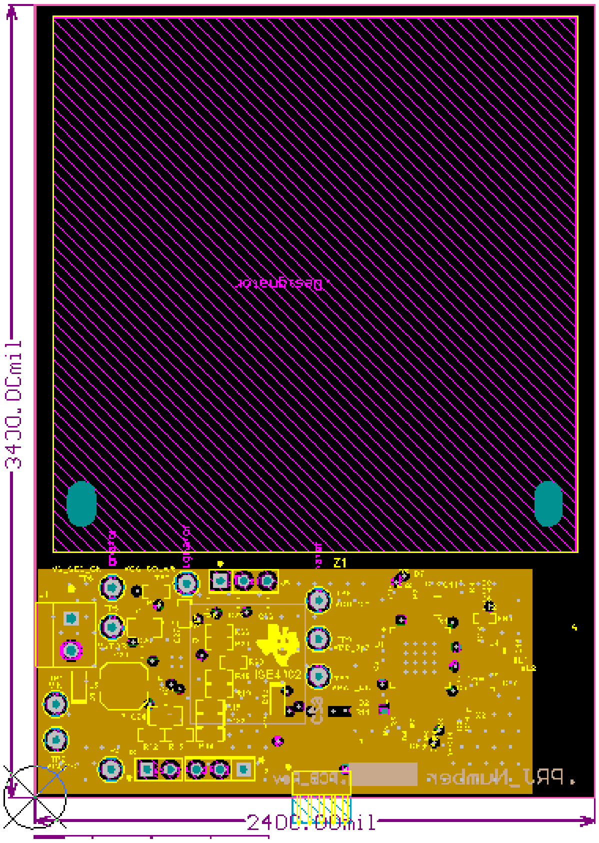


Figure 40. GND Layer

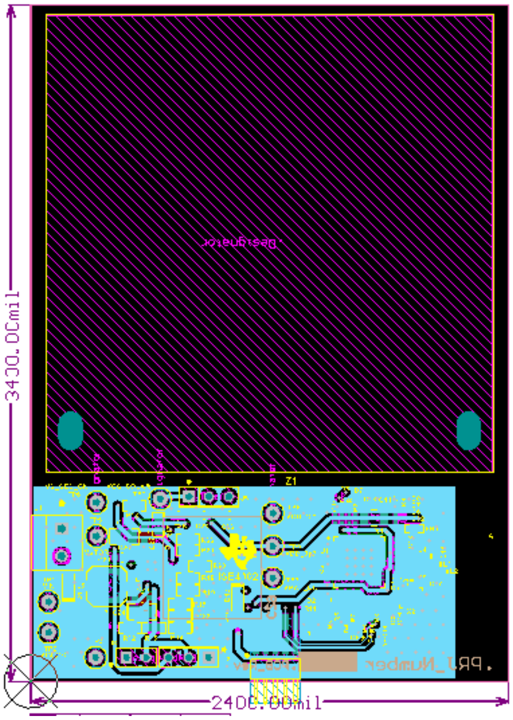


Figure 41. Power Layer

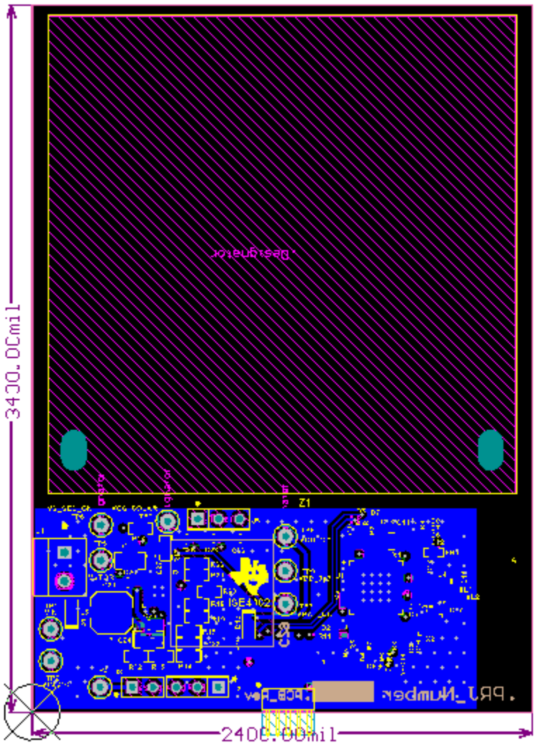
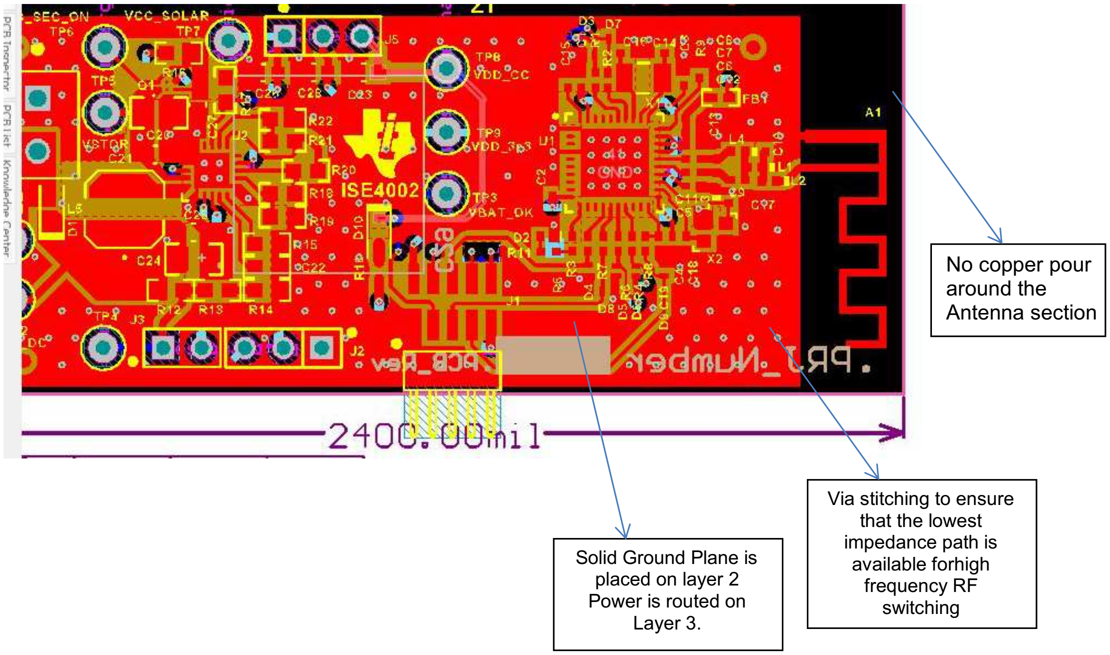


Figure 42. Bottom Layer

9.5 Layout Guidelines

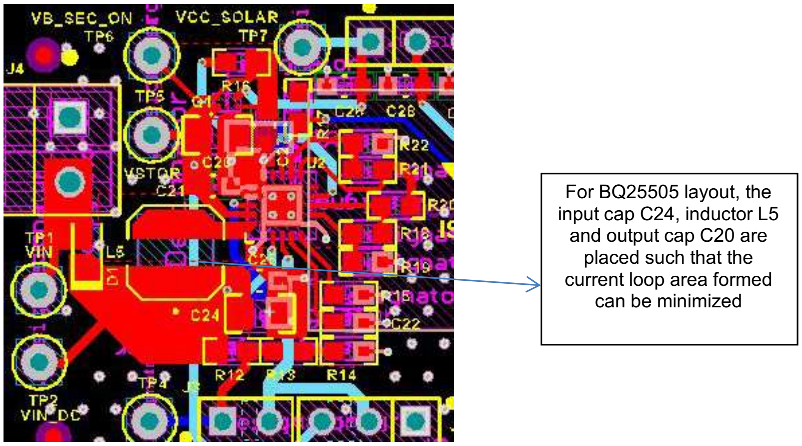


No copper pour around the Antenna section

Via stitching to ensure that the lowest impedance path is available forhigh frequency RF switching

Solid Ground Plane is placed on layer 2 Power is routed on Layer 3.

Figure 43.

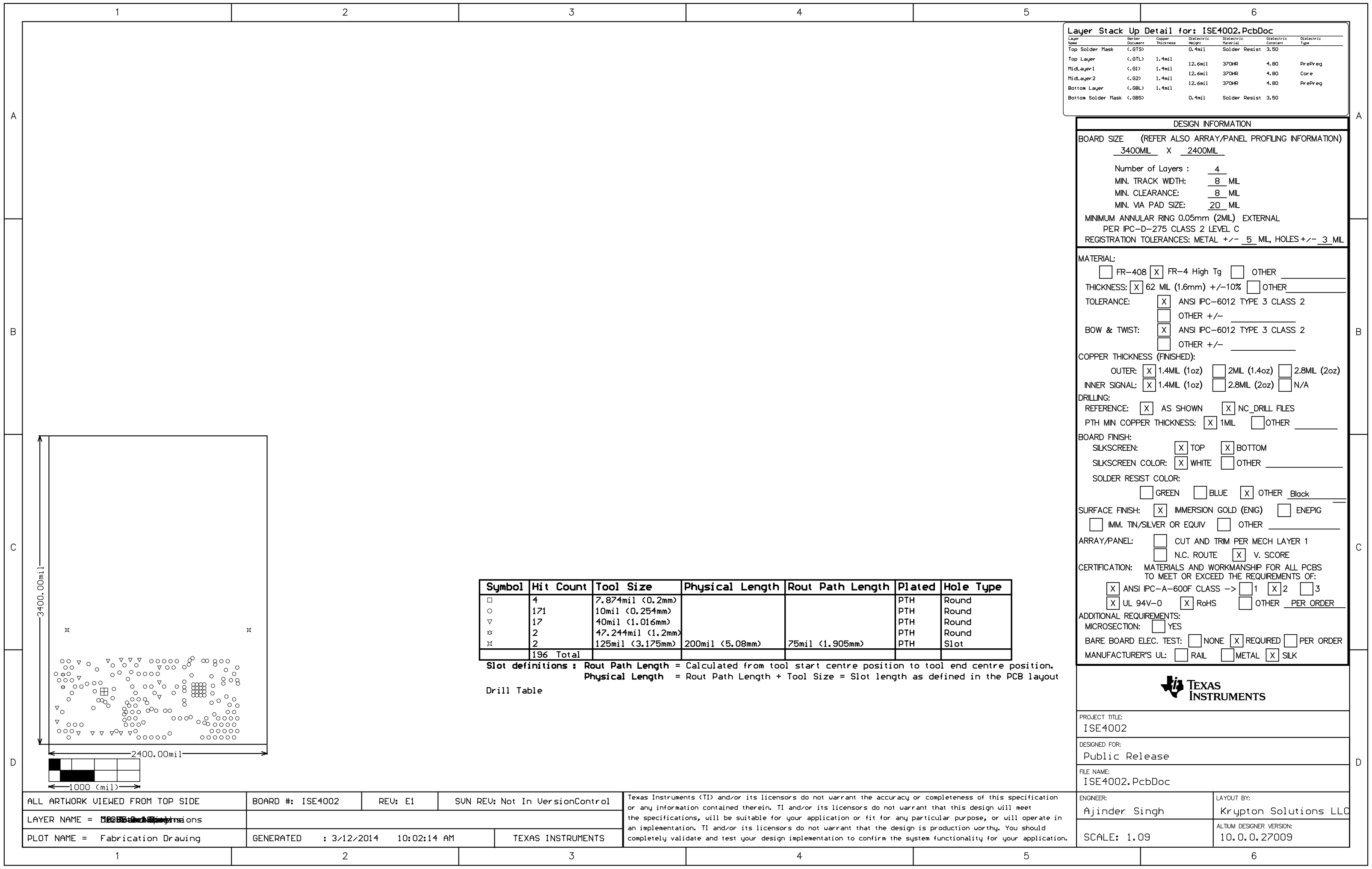


For BQ25505 layout, the input cap C24, inductor L5 and output cap C20 are placed such that the current loop area formed can be minimized

Figure 44.

9.6 Gerber Files

To download the Gerber files, see the design files at TIDA-00100



Layer Stack Up Detail for: ISE4002.PcbDoc

Layer Name	Gerber Document	Copper Thickness	Dielectric Height	Dielectric Material	Dielectric Constant	Dielectric Type
Top Solder Mask	(.GTS)		0.4mil	Solder Resist	3.50	
Top Layer	(.GTL)	1.4mil				
			12.6mil	370HR	4.80	PrePreg
MidLayer1	(.G1)	1.4mil				
			12.6mil	370HR	4.80	Core
MidLayer2	(.G2)	1.4mil				
			12.6mil	370HR	4.80	PrePreg
Bottom Layer	(.GBL)	1.4mil				
Bottom Solder Mask	(.GBS)		0.4mil	Solder Resist	3.50	

DESIGN INFORMATION

BOARD SIZE (REFER ALSO ARRAY/PANEL PROFILING INFORMATION)
3400MIL X 2400MIL

Number of Layers : 4
MIN. TRACK WIDTH: 8 MIL
MIN. CLEARANCE: 8 MIL
MIN. VIA PAD SIZE: 20 MIL
MINIMUM ANNULAR RING 0.05mm (2MIL) EXTERNAL
PER IPC-D-275 CLASS 2 LEVEL C
REGISTRATION TOLERANCES: METAL +/- 5 MIL, HOLES +/- 3 MIL

MATERIAL:
☐ FR-408 ☒ FR-4 High Tg ☐ OTHER
THICKNESS: ☒ 62 MIL (1.6mm) +/-10% ☐ OTHER
TOLERANCE: ☒ ANSI IPC-6012 TYPE 3 CLASS 2
☐ OTHER +/-
BOW & TWIST: ☒ ANSI IPC-6012 TYPE 3 CLASS 2
☐ OTHER +/-
COPPER THICKNESS (FINISHED):
OUTER: ☒ 1.4MIL (1oz) ☐ 2MIL (1.4oz) ☐ 2.8MIL (2oz)
INNER SIGNAL: ☒ 1.4MIL (1oz) ☐ 2.8MIL (2oz) ☐ N/A
DRILLING:
REFERENCE: ☒ AS SHOWN ☒ NC_DRILL FILES
PTH MIN COPPER THICKNESS: ☒ 1MIL ☐ OTHER
BOARD FINISH:
SILKSCREEN: ☒ TOP ☒ BOTTOM
SILKSCREEN COLOR: ☒ WHITE ☐ OTHER
SOLDER RESIST COLOR:
☐ GREEN ☐ BLUE ☒ OTHER Black
SURFACE FINISH: ☒ IMMERSION GOLD (ENIG) ☐ ENEPIG
☐ IMM. TIN/SILVER OR EQUIV ☐ OTHER
ARRAY/PANEL: ☐ CUT AND TRIM PER MECH LAYER 1
☐ N.C. ROUTE ☒ V. SCORE
CERTIFICATION: MATERIALS AND WORKMANSHIP FOR ALL PCBS TO MEET OR EXCEED THE REQUIREMENTS OF:
☒ ANSI IPC-A-600F CLASS -> ☐ 1 ☒ 2 ☐ 3
☒ UL 94V-0 ☒ RoHS ☐ OTHER PER ORDER
ADDITIONAL REQUIREMENTS:
MICROSECTION: ☐ YES
BARE BOARD ELEC. TEST: ☐ NONE ☒ REQUIRED ☐ PER ORDER
MANUFACTURER'S UL: ☐ RAIL ☐ METAL ☒ SILK

Symbol	Hit Count	Tool Size	Physical Length	Rout Path Length	Plated	Hole Type
□	4	7.874mil (0.2mm)			PTH	Round
○	171	10mil (0.254mm)			PTH	Round
▽	17	40mil (1.016mm)			PTH	Round
✡	2	47.244mil (1.2mm)			PTH	Round
¤	2	125mil (3.175mm)	200mil (5.08mm)	75mil (1.905mm)	PTH	Slot
	196 Total					

Slot definitions : Rout Path Length = Calculated from tool start centre position to tool end centre position.
Physical Length = Rout Path Length + Tool Size = Slot length as defined in the PCB layout

Drill Table

ALL ARTWORK VIEWED FROM TOP SIDE	BOARD #: ISE4002	REV: E1	SVN REV: Not In VersionControl
LAYER NAME = [illegible]			
PLOT NAME = Fabrication Drawing	GENERATED : 3/12/2014 10:02:14 AM		TEXAS INSTRUMENTS

Texas Instruments (TI) and/or its licensors do not warrant the accuracy or completeness of this specification or any information contained therein. TI and/or its licensors do not warrant that this design will meet the specifications, will be suitable for your application or fit for any particular purpose, or will operate in an implementation. TI and/or its licensors do not warrant that the design is production worthy. You should completely validate and test your design implementation to confirm the system functionality for your application.

PROJECT TITLE: ISE4002
DESIGNED FOR: Public Release
FILE NAME: ISE4002.PcbDoc
ENGINEER: Ajinder Singh
LAYOUT BY: Krypton Solutions LLC
SCALE: 1.09
ALTIUM DESIGNER VERSION: 10.0.0.27009

Figure 45. Fab Drawing

9.7 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00100

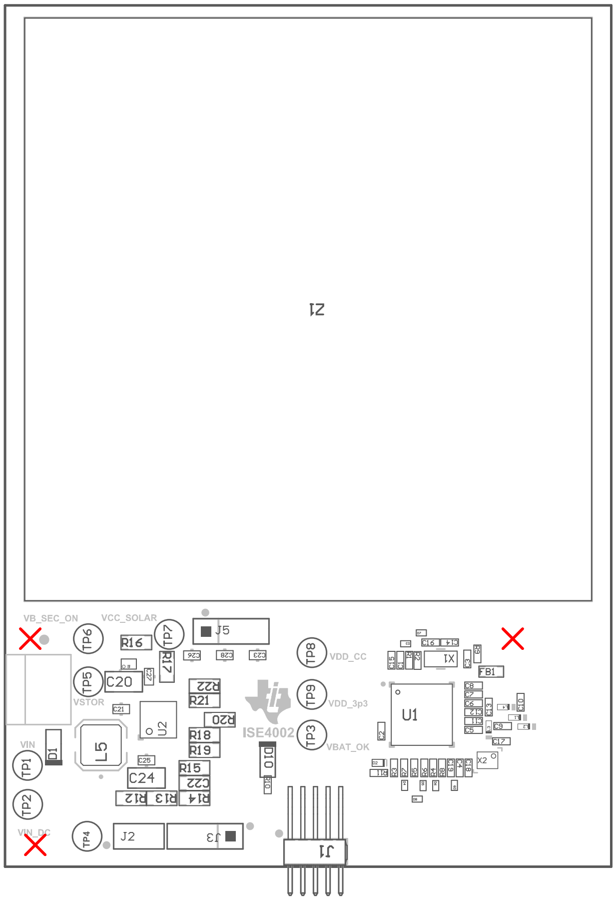


Figure 46.

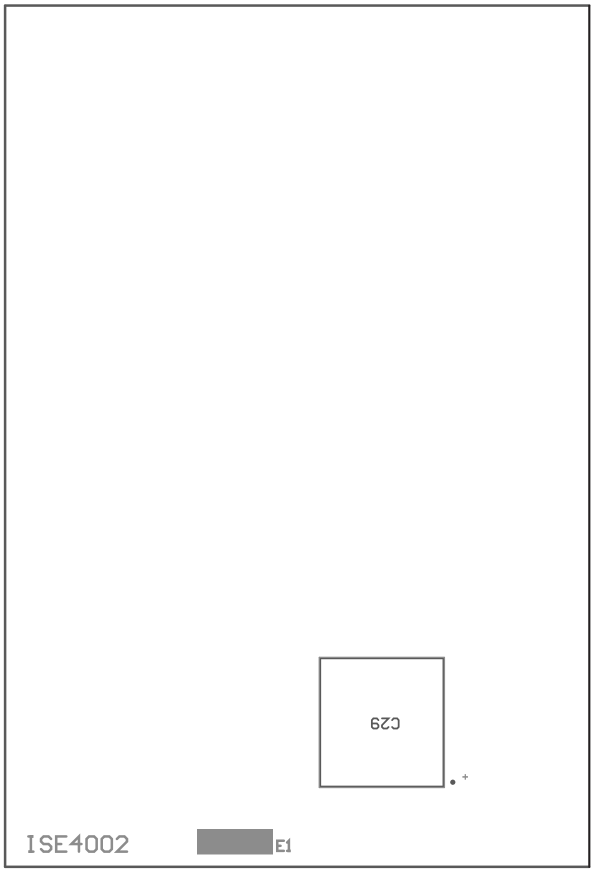


Figure 47.

9.8 Software Files

To download the software files for the reference design, see the design files at TIDA-00100

10 References

For additional references, see the following:

- bq25505 Data sheet
- CC2541 Data sheet
- CSD75205W1015 Data sheet

11 About the Author

AJINDER PAL SINGH is a Systems Architect at Texas Instruments, where he is responsible for developing reference design solutions for the industrial segment. Ajinder brings to this role his extensive experience in high-speed digital, low-noise analog and RF system-level design expertise. Ajinder earned his Master of Science in Electrical Engineering (MSEE) from Texas Tech University in Lubbock, TX. Ajinder is a member of the Institute of Electrical and Electronics Engineers (IEEE).

Revision History

Changes from Original (March 2014) to A Revision **Page**

- Deleted variable "R_{OK3}". 12

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

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