TI Designs
Energy Harvesting for Wireless Switch—Power Reference Design

Description

The TIDA-00690 is an Energy Harvesting design for wireless switch. The switch is built like a linear dynamo and transforms the mechanical energy into electrical energy. This electrical energy is harvested in an optimal manner by the TIDA-00690, thus allowing: wireless position control of valves or other mechanical actuators, emergency switches, and a controller for machines start and stop.

In addition, being wireless and cableless increases flexibility and uptime by example when mechanical vibration or chemically aggressive environment could render wires impractical.

Wireless switches can also be deployed more cost effectively when a factory or a plant retrofit is considered.

Resources

TIDA-00690	Design Folder
TPS62122	Product Folder
TPS62125	Product Folder

Features

- Energy Harvested: > 0.16 mJ (Over 15 ms)
- BLE Beacon Transmission on Three Channels (8 Byte per Channel)
- Cableless (No Power or Data Cable
- Reduced Maintenance Costs
- Temperature Range: –40°C to 85°C

Applications

- Factory Automation
- Process Control
- Field Actuators
- Field Transmitters

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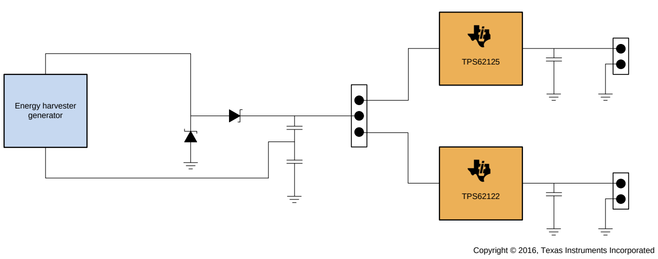

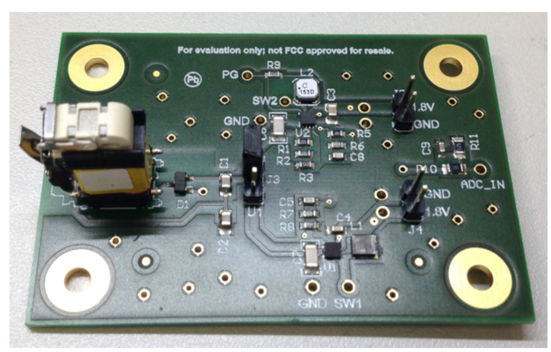

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1 System Overview

1.1 System Description

The TIDA-00690 offers a power management solution for energy harvesting switches. EH switches transform the mechanical input energy of the actuation into electrical energy. They are suitable when lower maintenance and installation costs, increased flexibility, and system uptime are required and when wiring is considered impractical. Furthermore, they are a potential solution for explosive proof applications thanks to their inherent low-power operating characteristics that allows avoiding the usage of intrinsically-safe barriers, encapsulation or other expensive protection method[1].

Their applications span from factory automation and process control to building automation as well as in non-industrial areas.

This reference design targets especially those applications where on-off signals for machine start and stop control, presence and position sensing, counting, alarm signaling, and other desired digital inputs are required[1].

The TIDA-00690 can be interfaced to the SimpleLink™ CC2650 Wireless MCU LaunchPad™ Kit to transmit wireless data through the CC2650 that is powered by either the TPS62122 or the TPS62125 present on the board.

The buck converter regulates the rectified and doubled signal coming from the switch, feeding the output voltage to the CC2650. A voltage doubler is used at the input of the buck converter to charge capacitors from the switch output voltage and switch these charges in such a way that, ideally, exactly twice the voltage is produced at the output as at its input.

1.2 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
Output voltage	1.8 V	Section 2.2
Energy harvested (over 15 ms)	At least 0.16 mJ	Section 3.1
Temperature range	–40°C to 85°C	—

1.3 Block Diagram

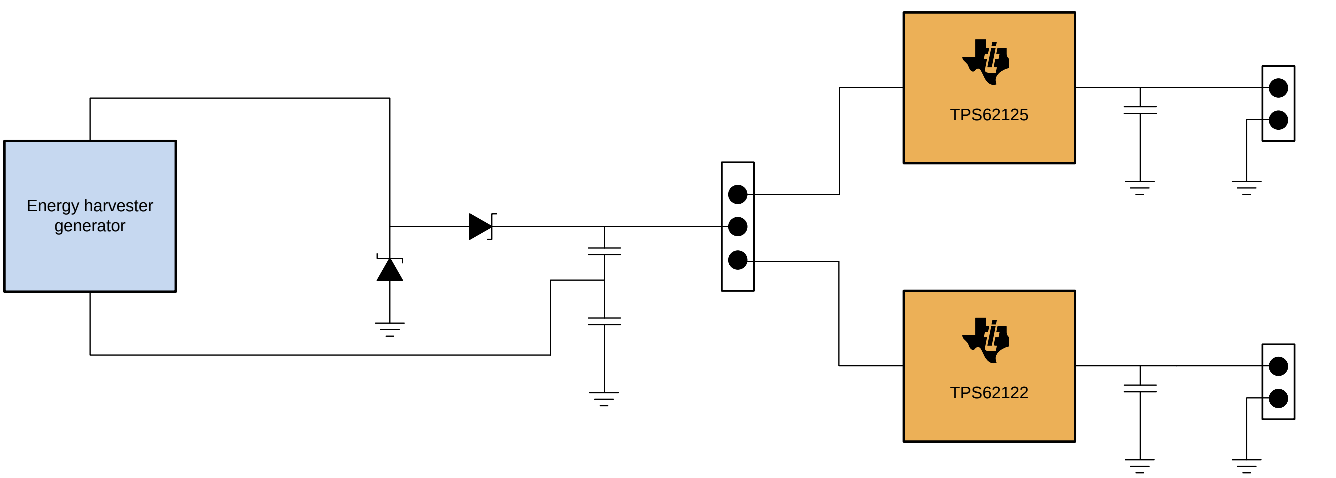


Figure 1. TIDA-00690 Block Diagram

1.4 Highlighted Products

1.4.1 TPS62122

Features:

- Wide input voltage range: 2 to 15 V
- Up to 96% efficiency
- Power save mode with 11-µA quiescent current
- Output current: 75 mA
- Output voltage range: 1.2 to 5.5 V
- Up to 800-kHz switch frequency
- Synchronous converter, no external rectifier
- Low output ripple voltage
- 100% duty cycle for lowest dropout
- 2-mm × 2-mm DFN 6-pin (TPS62122) package
- Internal soft start
- 2.5-V rising and 1.85-V falling UVLO thresholds

The TPS6212x device is a highly efficient synchronous step-down DC-DC converter optimized for low-power applications. The device supports up to 75-mA output current and allows the use of tiny external inductors and capacitors.

The wide operating input voltage range of 2 to 15 V supports energy harvesting, battery powered and as well 9-V or 12-V line powered applications.

With its advanced hysteretic control scheme, the converter provides power save mode operation. At light loads, the converter operates in pulse frequency modulation (PFM) mode and transitions automatically in pulse width modulation (PWM) mode at higher load currents. The power save mode maintains high efficiency over the entire load current range. The hysteretic control scheme is optimized for low output ripple voltage in PFM mode in order to reduce output noise to a minimum. The device consumes only 10 µA of quiescent current from VIN in PFM mode operation.

In shutdown mode, the device is turned off.

The TPS6212x operates over an free air temperature range of –40°C to 85°C. The TPS62122 is available in a 2 mm × 2 mm 6-pin DFN package.

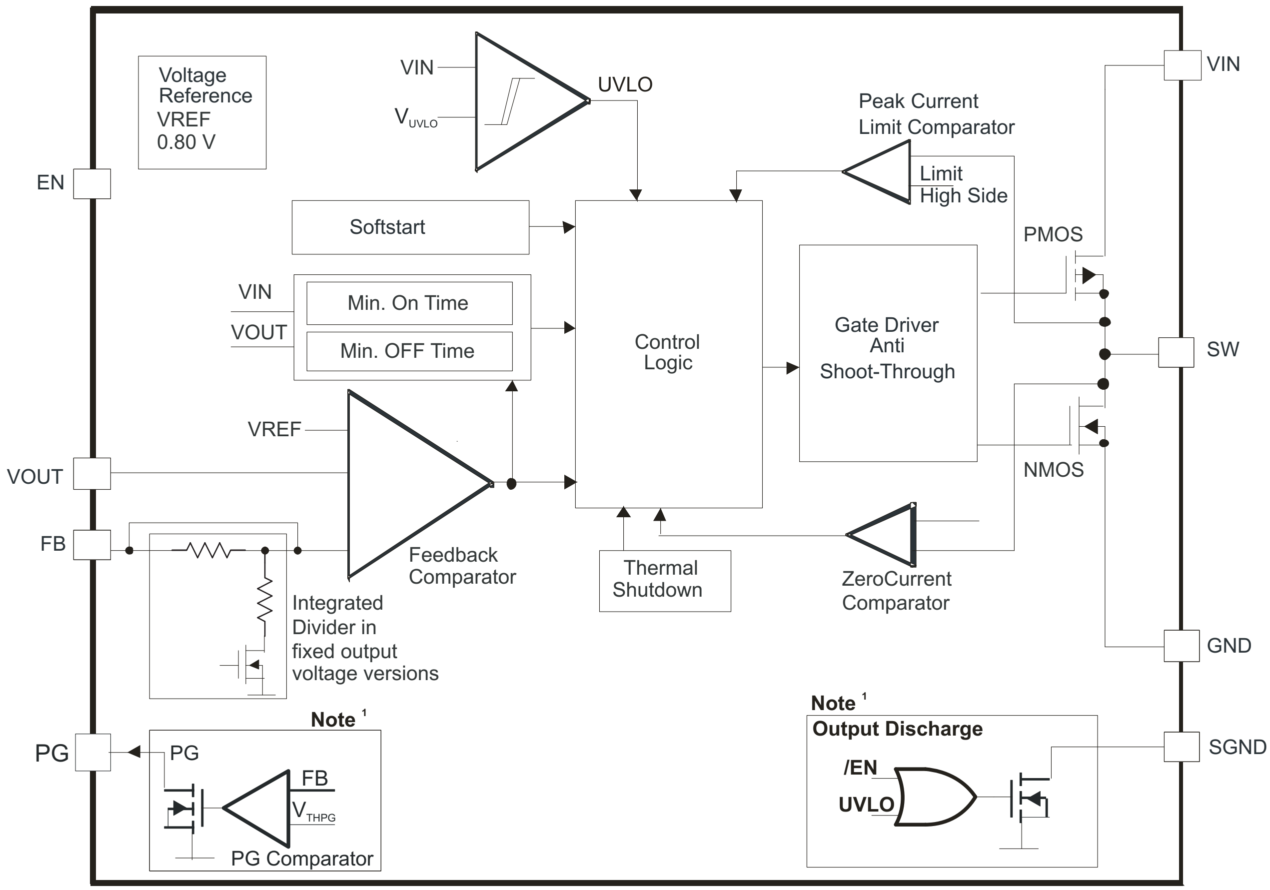


Figure 2. TPS62122 Functional Block Diagram

1.4.2 TPS62125

Features:

- Wide input voltage range: 3 to 17 V
- Input supply voltage supervisor (SVS) with adjustable threshold and hysteresis consuming typical 6-µA quiescent current
- Wide output voltage range: 1.2 to 10 V
- Typical 13-µA quiescent current
- 350-nA typical shutdown current
- Seamless power save mode transition
- DCS-Control™ scheme
- Low output ripple voltage
- Up to 1-MHz switching frequency
- Highest efficiency over wide V_{IN} and V_{OUT} range
- Pin-to-pin compatible with TPS62160/TPS62170
- 100% duty cycle mode
- Power good open drain output
- Output discharge function
- Small 2-mm × 2-mm 8-pin WSON package

The TPS62125 device is a high-efficiency synchronous step-down converter optimized for low- and ultra-low-power applications providing up to a 300-mA output current. The wide input voltage range of 3 to 17 V supports 4-cell alkaline and 1- to 4-cell Li-Ion batteries in series configuration as well as 9- to 15-V powered applications. The device includes a precise low-power enable comparator, which can be used as an input SVS to address system specific power-up and power-down requirements. The enable comparator consumes only 6-µA quiescent current and features an accurate threshold of 1.2 V typical as well as an adjustable hysteresis. With this feature, the converter can generate a power supply rail by extracting energy from a storage capacitor fed from high impedance sources such as solar panels or current loops. With its DCS-Control scheme the converter provides power-save mode operation to maintain highest efficiency over the entire load current range. At light loads the converter operates in PFM mode and transitions seamlessly and automatically in PWM mode at higher load currents. The DCS-Control scheme is optimized for low-output ripple voltage in PFM mode in order to reduce output noise to a minimum and features excellent AC load regulation. An open-drain power good output indicates once the output voltage is in regulation.

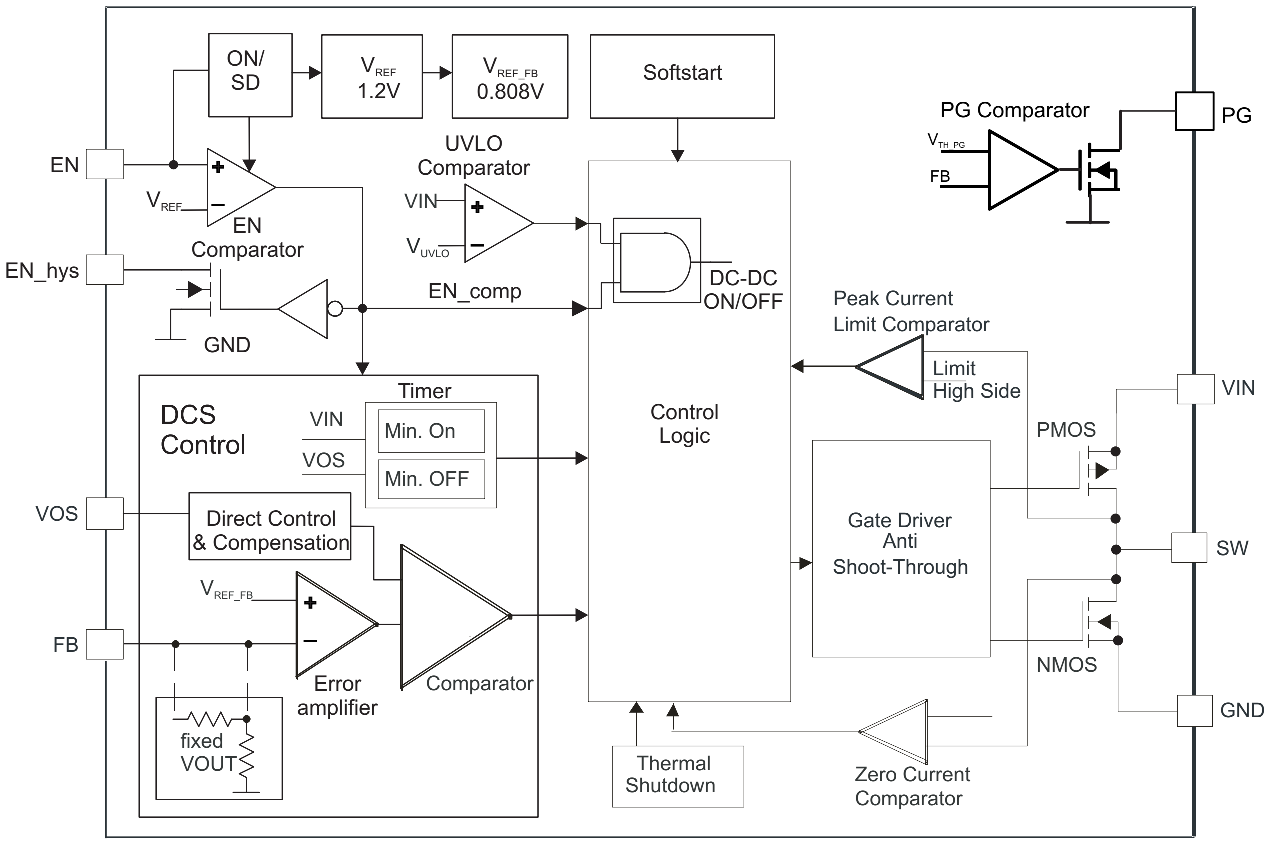


Figure 3. TPS62125 Functional Block Diagram

2 System Design Theory

2.1 Theory of Operation

This section provides the following generic background information to facilitate the understanding of this TI Design:

- Energy harvesting
- Kinetic harvesting
- Energy harvesting switch
- Ultra-low-power design guidelines

2.1.1 Energy Harvesting

Energy harvesting is the process by which energy is derived from external sources (for example, solar power, thermal energy, wind energy, kinetic energy, and so on), captured, and stored to be used by wireless autonomous devices that transmit information[2].

Energy harvesters provide a very small amount of energy that comes from the surrounding ambient (for example, sun, wind, heat, and electromagnetic). Electronic devices need to extract and manage this small amount of energy to make it usable for the wireless application. However, nowadays most of the wireless applications are battery powered, requiring periodically maintenance due to the limited battery lifetime and extra cost. The use of energy harvesters would allow to reduce and in some cases eliminate the use of batteries.

The TIDA-00690 operates without any batteries or external power supply, exploiting the only energy generated by the EH switch in order to wirelessly transmit the needed information.

2.1.2 Kinetic Harvesting

Kinetic energy is the energy generated by a motion of an object. In this specific case, the object is a magnet that moves back and forward inside a coil changing the magnetic field and so induce a voltage in the coil. This principle is well known as an electromagnetic induction, or Faraday's law, from the name of his inventor.

Since the 19th century, the most common application of Faraday's law has been the bicycle dynamo, which has been a reliable and easy-to-manufacture device that has kept bicycle lights going in the night for decades[3].

The energy harvesting switch from ZF transforms the mechanical input energy of the actuation into electrical energy. The advantages of the system are that the switch can be placed anywhere without the need for any wires. Over its whole life cycle, it will fulfill its function completely maintenance free and without any need to replace a battery[4].

2.1.3 ZF Energy Harvesting Switch

The inductive energy converter consists of an electromagnetic generator, which changes the magnetic flux in the coils by a sudden movement of a magnet, thus creating an electric impulse through the actuation of the wireless switch module. The switch is small and has a very compact size and high energy output[4].

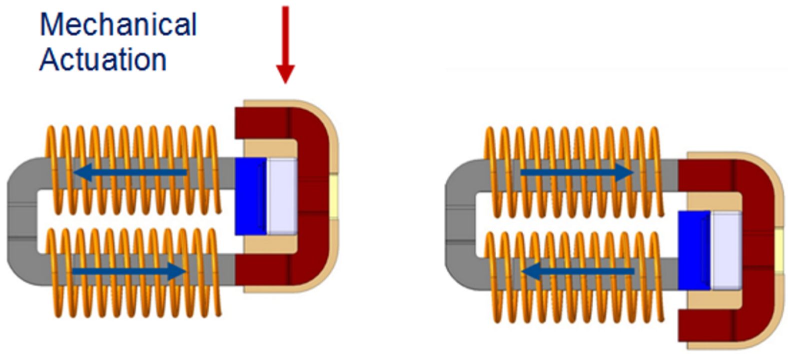


Figure 4. RF Mechanical Actuation

Table 2. Key System ZF Switch Specifications

PARAMETER	SPECIFICATIONS
Actuating force	6 N
Actuating stroke	4 mm
Lifetime	< 1 m
Power typ	400 µJ
Temperature	–40°C to 85°C

2.1.4 Ultra-Low-Power Design Guidelines

With the advent of wireless technology, more and more stringent power consumption requirements are needed. Furthermore, the usage of batteries is becoming a concern due to the required maintenance and extra cost added to the system.

Energy harvesting with breakthrough TI technology allows the development of systems that extract and manage nanopower from a variety of sources such as solar, thermal electric, electromagnetic, and vibration energy.

The TIDA-00690 uses either the TPS62125 or the TPS62122 to convert the electrical energy coming from the switch into a predefined voltage. The wide input voltage of these two converters makes these devices suitable for this kind of application due to the fact that losses are reduced at the minimum. Considering an input voltage like the one in Figure 5, the ideal case would be to reduce as much as possible the unused energy.

The TPS62125 and TPS62122 consume very low quiescence current. This is important because this is the overhead current required to operate just the DC-DC converter and it is the current thrown away just to begin converting the power. It is preferable to not throw away too much of the harvested energy, so a low quiescent current is important when selecting the device.

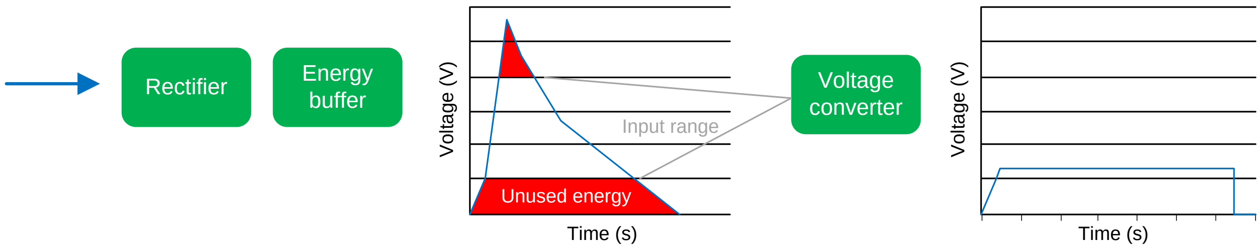


Figure 5. Wide Input Voltage Converter to Reduce Losses

2.1.5 Ultra-Low-Power Wireless MCU

The CC2650 is a wireless MCU targeting *Bluetooth*® Smart, ZigBee® and 6LoWPAN, and ZigBee RF4CE remote control applications.

The device is a member of the CC26xx family of cost-effective, ultra-low-power, 2.4-GHz RF devices. The devices' very low-active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin cell batteries and in energy-harvesting applications.

The CC2650 contains a 32-bit ARM® Cortex®-M3 processor that runs at 48 MHz as the main processor and a rich peripheral feature set that includes a unique ultra-low-power sensor controller. This sensor controller is ideal for interfacing external sensors and for collecting analog and digital data autonomously while the rest of the system is in sleep mode. Thus, the CC2650 is ideal for applications within a whole range of products including industrial, consumer electronics, and medical.

The *Bluetooth* Low Energy (BLE) controller and the IEEE 802.15.4 MAC are embedded into ROM and are partly running on a separate ARM Cortex-M0 processor. This architecture improves overall system performance and power consumption and frees up flash memory for the application.

The *Bluetooth* Smart and ZigBee stacks are available free of charge from www.TI.com.

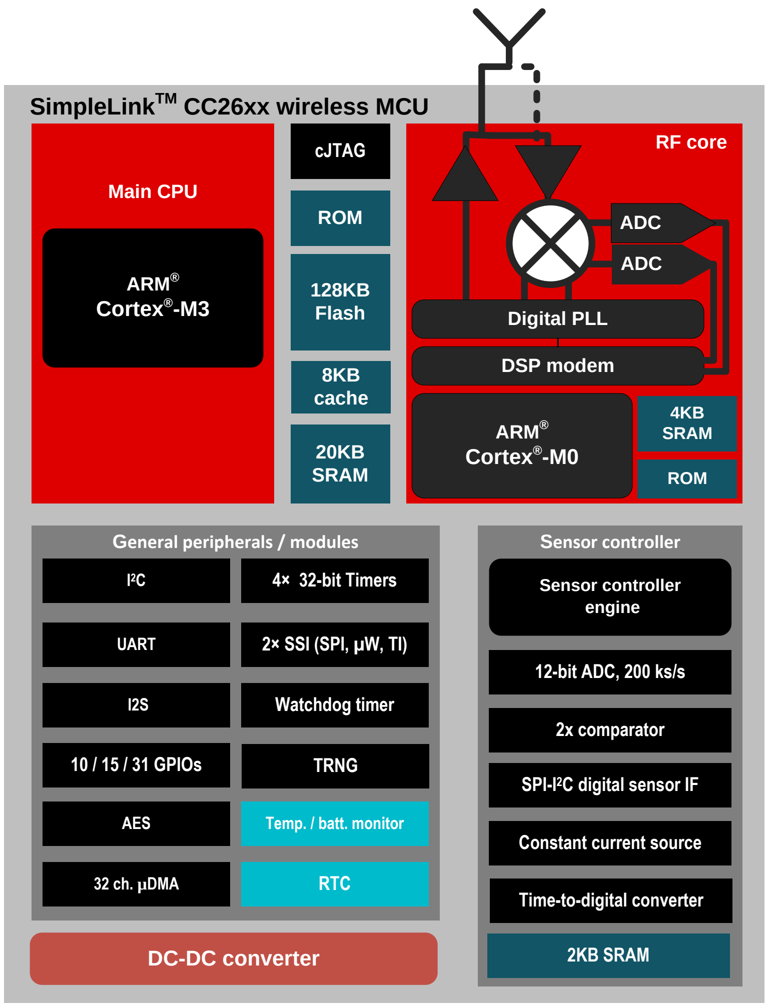


Figure 6. CC2650 Functional Block Diagram

2.2 Design Considerations

2.2.1 Rectifier and Energy Buffer

When designing an energy harvesting circuit, the challenge is to extract the maximum amount of energy regardless of the load to have a flexible design, which can be reused across multiple systems.

A electrodynamic system can be seen a generator with an fixed output impedance, so in theory to maximize the energy extraction, one only has to match the source impedance with the load. However, for a dynamically behaving load, this is not possible.

An alternative is to buffer the energy so it can be given as a constant supply to the active load. The challenge is then to be able to still extract as much energy from the generator without exposing a constant load.

In absence of formal solutions to the challenge, consider it from an intuitive standpoint:

- By leaving the input cap of the DC-DC charge for as long as possible, no energy is extracted anymore as soon as the output voltage of the generator would go below the voltage of the input cap.
- By enabling the DC-DC to start as soon as possible, the generator is operating as close as possible to its short circuit operating point, which is also further away from it maximum power point.

Another design consideration to keep in mind is that the generator will generate two pulses: one positive and one negative for each full actuation (push and release). This TI Design maximizes energy extraction by going for the rectification of the negative wave.

For the rectification, two options are possible: either a full-wave rectification or a voltage doubler. This TI Design follows the voltage doubler option for two reasons:

- A voltage double has only half of the diode loses compared to a full-wave rectifier, so the overall efficiency is increased.
- The energy left in a cap when the DC-DC reaches its UVLO can be considered lost. With a full-wave rectifier, this is always the case. With a voltage doubler, the second wave will charge the cap on top of the UVLO level and thus will be fully used.

Finally, the input cap value in function of the UVLO voltage was optimized through trial and error with an optimization goal of maximizing the run time of the DC-DC (that is, the time for which it is providing a valid voltage on its output).

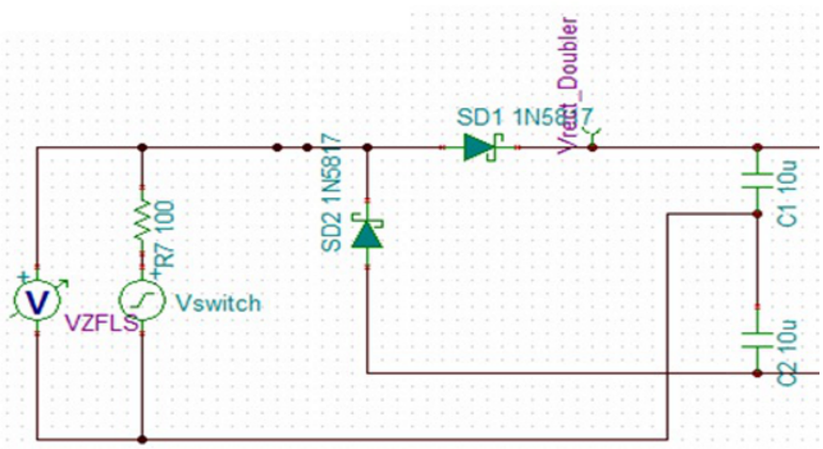


Figure 7. Rectifier and Energy Buffer

2.2.2 TPS62125 Design Considerations

The circuitry of the TPS62125 follows its datasheet recommendations (SLVSAQ5). C6 is the input bypass capacitors; C8, C3, and L2 are the respective components of output filter, using the values of Table 3 inside the TPS62125 datasheet . R5 and R6 are used to set the output voltage according to Table 2 in the datasheet to the desired 1.8 V. R1 (255k), R2 (200k), and R3 (51k) provide an easy way to define a precise level for VIN_DCDC at which the high efficiency DC/DC converter starts switching, but defines also a stop-voltage level. By having those two voltages programmable, a certain hysteresis can be implemented for the start and stop of the converter. With the values given for the three resistors, the startup and stop values are equal respectively to 2.73 V and 2.3 V, reducing the energy losses as much as possible.

2.2.3 TPS62122 Design Considerations

The circuitry of the TPS62122 follows its datasheet recommendations (SLVSAD5). C7 is the input bypass capacitors; C5, C4, and L1 are the respective components of output filter, using the values of Table 2 inside the TPS62122 datasheet. R7 and R8 are used to set the output voltage according to Table 1 in the datasheet to the desired 1.8 V.

2.2.4 Simulations

Simulations of the application have been performed with TINA-TI for both the TPS62122 and the TPS62125. The model of the two converters can be found in the landing page of their respective product pages.

A model of the switch has been designed considering a typical peak voltage of 9 V, which is positive when the switch is pressed and negative when the switch is released. Around 100 ms is considered between the two events (press and release). This can vary depending on how fast the switch is pressed.

The simulations have been performed with a 300-Ω load at the output of the converter.

The red curve in Figure 8 and Figure 9 represents the voltage generated by the switch, the green curve is the voltage at the input of the converter, and the yellow curve is the voltage at the output of the converter.

The output voltage is regulated at 1.8 V, and while the first output pulse corresponds to the button press, the second one corresponds to the button release.

As it is possible to see from Figure 8 and Figure 9, the second pulse is longer than the first one because when the button is released there is still some energy left in the capacitor.

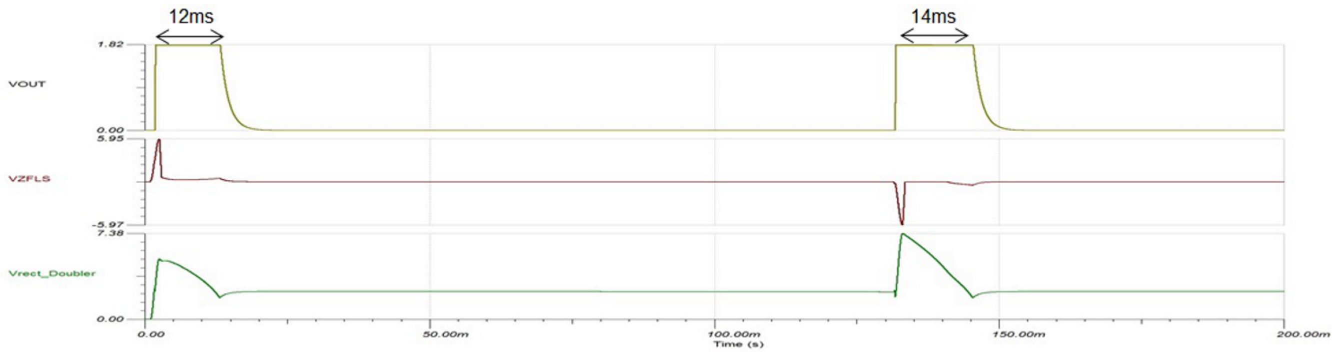


Figure 8. TPS62122 Simulations

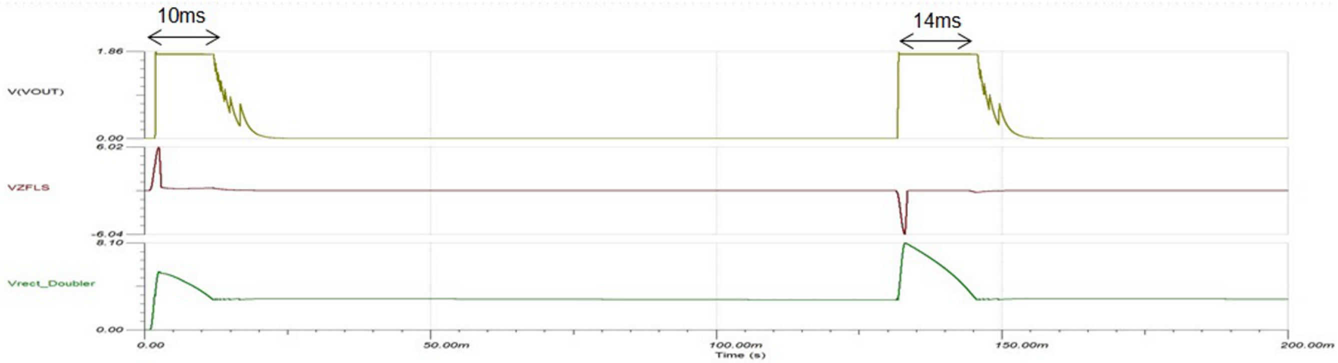


Figure 9. TPS62125 Simulations

3 Testing and Results

Two main tests were performed, one connecting to the TIDA-00690 output a resistive load and the other one connecting the SimpleLink CC2650 Wireless MCU LaunchPad Kit. In both tests, the input and output voltage of the converter, the voltage at the switch node of the converter, and the output current were monitored.

When the TIDA-00690 is connected to the SimpleLink CC2650 Wireless MCU LaunchPad Kit, the simple BLE Broadcaster sample application was used to transmit data wirelessly.

3.1 Tests With Resistive Load

For this test, a 300-Ω resistor has been connected at the output of the TIDA-00690.

In Figure 10 is shown, the input (red) and output (blue) voltage of the TPS62122. As expected, the output voltage is regulated at 1.8 V, and while the first output pulse corresponds to the button press, the second one corresponds to the button release.

As it is possible to see from Figure 10, the second pulse is longer than the first one due to the fact that when the button is released there is still some energy left in the capacitor.

In order for the microcontroller to recognize when the button is pressed and released, it is possible to connect the output of the generator to a two-microcontroller GPIO with two diodes each conducting in either the first half or the second half.

To ensure voltage level compatibility some resistor divider has to be put between the diodes and the GPIO. The resistors have to be chosen so that when the half wave is at its peak, the voltage in the middle is no higher than 1.8 V (for the positive half wave) and no lower than 0 V for the negative half wave.

Considering a 300-Ω load resistor and an output voltage equal to 1.8 V, the output current is 6 mA. The energy harvested when the button is pressed is equal to 0.14 mJ (over 13 ms) while when it is released is equal to 0.16 mJ (over 15 ms).

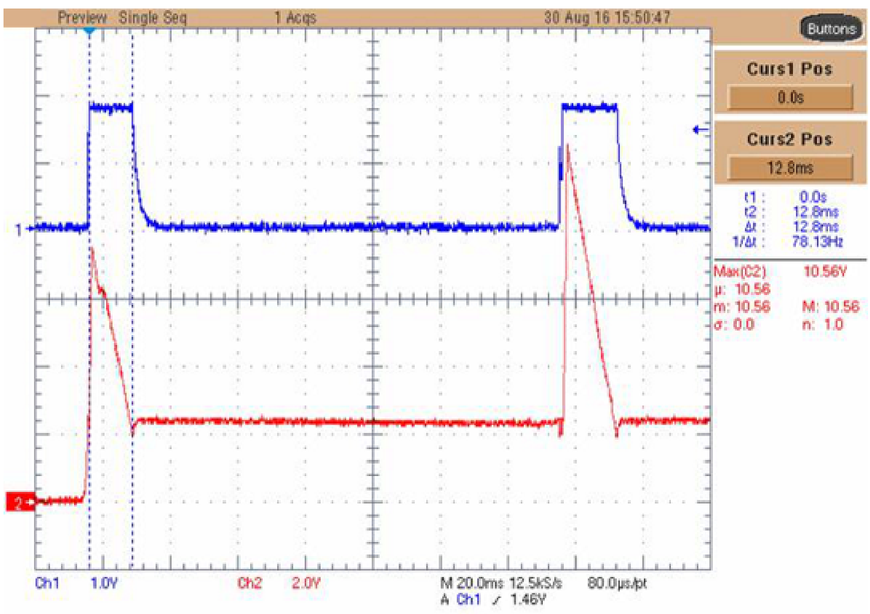


Figure 10. TPS62122—V_{IN} (Red), V_{OUT} (Blue) With 300-Ω Load

To measure the voltage at the switch node of the converter, a probe with ground spring is used. Due to the low output current, the TPS62122 is going to operate in discontinuous current mode (DCM).

To show the DCM, Figure 11 provides a good orientation by different states, labeled from A to E:

- **A**: The high-side FET (between the VIN pin and SW pin) is ON. As a result, the V_{IN_DCDC} can be measured on the switch node SW2, and inductor current flows through the high-side FET and rises.
- **B**: The high-side FET goes OFF, and the low-side FET (also called Sync-FET) is ON, basically connecting SW2 to GND_iso through its low $R_{DS(ON)}$, inductor current flows through the low-side FET and declines.
- **C**: Both FETs are OFF, and inductor needs to flow through the body diode of the low-side FET, causing a negative voltage on SW2 that equals the forward voltage of this body diode.
- **D**: Both FETs are OFF, the inductor current has declined to zero, and the inductor forms together with the parasitic capacitances connected to the inductor a resonant tank. The resonant ringing, which is a characteristic for any switching converter operating in DCM, starts and decreases with the diminishing energy of the resonant tank. Due to the small inductance and capacitance values, the energy is limited and does not usually create EMI issues. The average or DC level of the ringing equals the output voltage V_{OUT_DCDC} (which is connected to the other side of the inductor).
- **E**: All the energy of the resonant tank is dissipated. Ringing has stopped. Both FETs are OFF. The output voltage is still connected to the inductor and can therefore be seen on SW2.

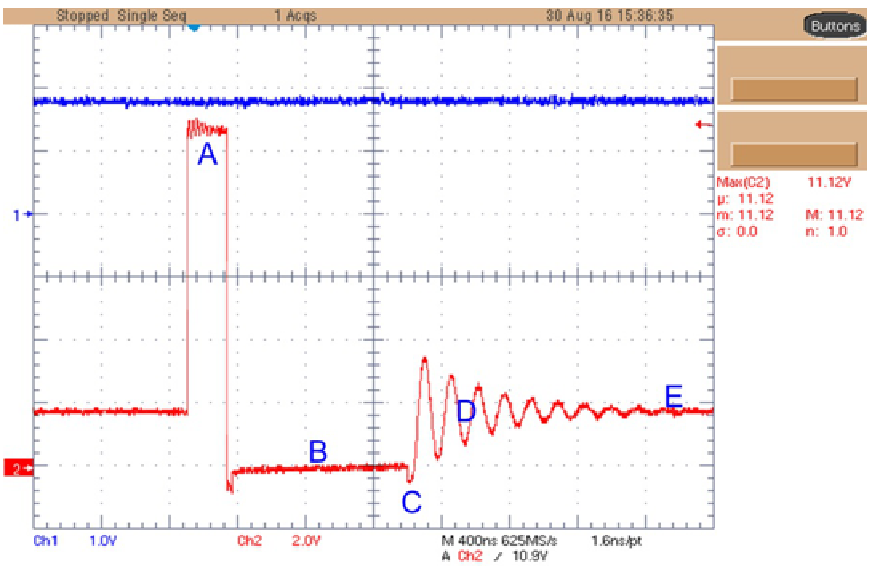


Figure 11. TPS62122—Switch Node Voltage Waveform (Red), V_{OUT} (Blue) With 300-Ω Load

Very similar results have been obtained with the TPS62125 as shown in Figure 12 and Figure 13.

Considering a 300-Ω load resistor and an output voltage equal to 1.8 V, the output current is 6 mA. The energy harvested when the button is pressed is equal to 0.12 mJ (over 11 ms) while when it is released is equal to 0.21 mJ (over 20 ms).

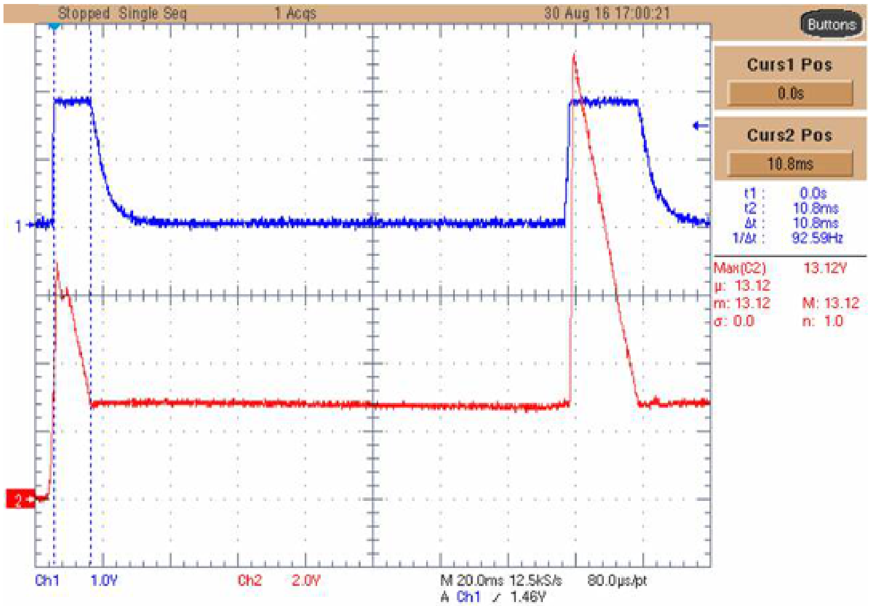


Figure 12. TPS62125—V_{IN} (Red), V_{OUT} (Blue) With 300-Ω Load

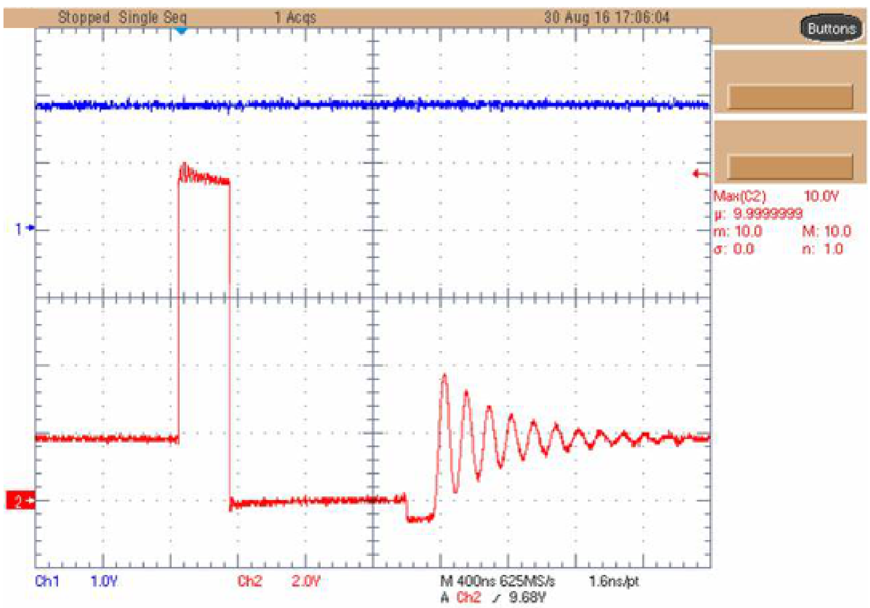


Figure 13. TPS62125—Switch Node Voltage Waveform (Red), V_{OUT} (Blue) With 300-Ω Load

3.2 Test With SimpleLink CC2650 Wireless MCU LaunchPad Kit

For this test, the SimpleLink CC2650 Wireless MCU LaunchPad Kit has been connected at the output of the TIDA-00690 as shown in Figure 14.

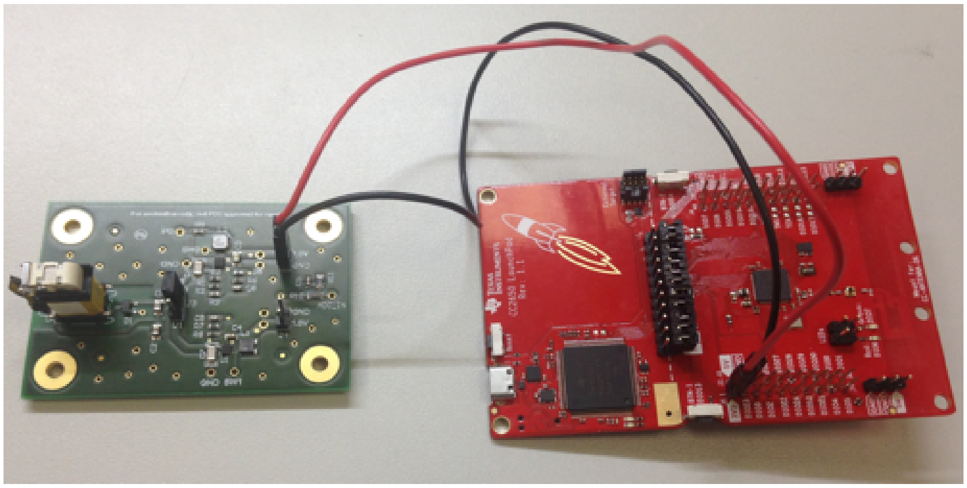


Figure 14. Test Setup

The simple BLE Broadcaster sample application code was used to transmit data wirelessly.

The CC2650 sends out non-connectable advertisement packets that contain eight bytes of data.

An advertising event is where the *Bluetooth* Smart peripheral device broadcasts information to either share information or become connected to a *Bluetooth* Smart Ready Central device, such as a smart phone. The device wakes up and broadcasts packets on three separate channels. For a non-connectable beacon, there are no RX states during the advertising event, which reduces the power consumption further.

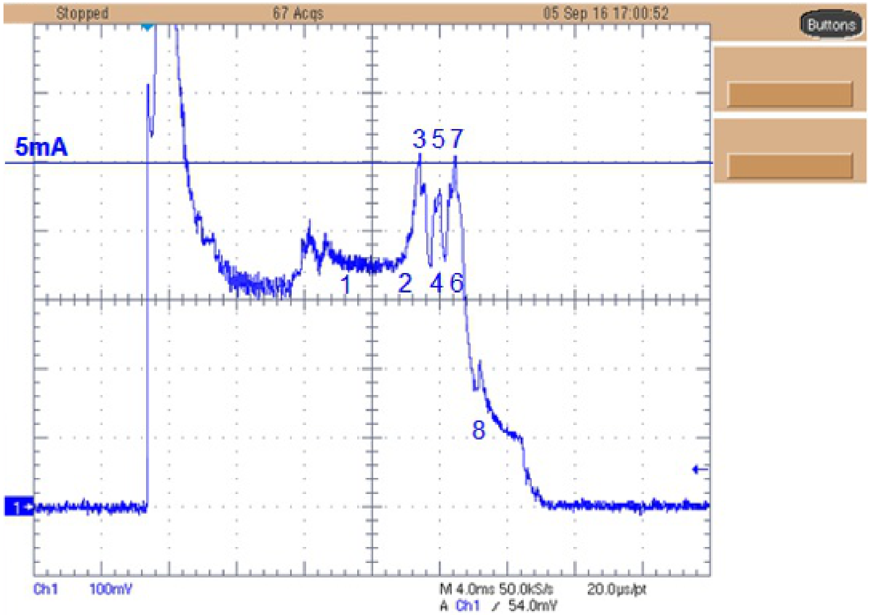


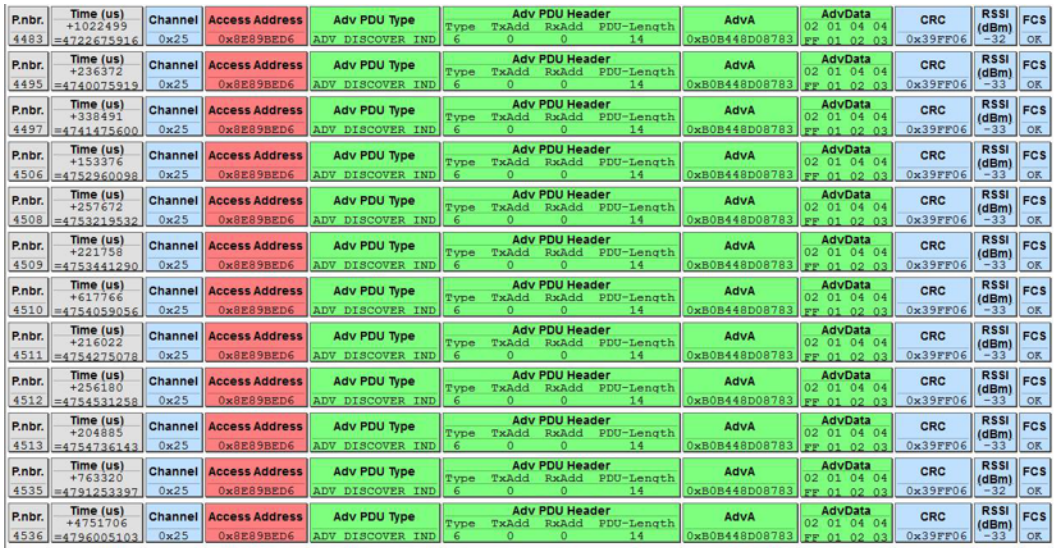
Figure 15. Beacon Event

Table 3. Beacon Event, State Analysis

STATE NUMBER	STATE	TIME (µs)	CURRENT (mA)	COMMENTS
1	Pre-processing	4880	3.5	RTOS wake-up, radio setup, XTAL guard time
2	Radio preparation	320	4.0	Radio is turned on and in transition to TX
3	TX	160	5.2	The radio transmits an advertisement packet on Channel 37. Time is dependent on amount of transmitted data
4	TX-to-TX transition	240	4.5	TX to TX transition
5	TX	160	5.2	The radio transmits an advertisement packet on Channel 38. Time is dependent on amount of transmitted data
6	TX-to-TX transition	240	4.5	TX to TX transition
7	TX	160	5.2	The radio transmits an advertisement packet on Channel 39. Time is dependent on amount of transmitted data
8	Post-processing and going to standby	2320	2.0	BLE protocol stack sets up the sleep timer in preparation for the next event, and then going to standby afterwards

To verify the proper operation of the radio transmission, the CC2540EMK-USB CC2540 USB Evaluation Module Kit is used to sniff packets using the SmartRF Protocol Packet Sniffer software. After installing the Packet Sniffer software (v2.18.1 at the time of writing), the procedure is as follows to detect the data transmissions:

1. Plug the CC2540EMK-USB into an unused USB port on the computer with the Packet Sniffer software installed.
2. Open the Packet Sniffer software, choose BLE as the protocol, and hit Start.
3. Click the Radio Configuration tab on the bottom toolbar and select 37 for the Advertising Channel.
4. Press the Play button on the top toolbar to initiate the packet capture process.
5. There will likely be many other packets detected, probably from mobile phones and other devices that use the *Bluetooth* Smart protocol. To view only the packets sent from the TI Design hardware, apply a display filter. Figure 16 shows a sample display of what will be recorded. In the field AdvData, there are 8 bytes.



P.nbr.	Time (us)	Channel	Access Address	Adv PDU Type	Adv PDU Header Type	TxAdd	RxAdd	PDU-Length	AdvA	AdvData	CRC	RSSI (dBm)	FCS
4483	+1022499 =4722675916	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-32	OK
4495	+236372 =4740075919	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-33	OK
4497	+338491 =4741475600	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-33	OK
4506	+153376 =4752960098	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-33	OK
4508	+257672 =4753219532	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-33	OK
4509	+221758 =4753441290	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-33	OK
4510	+617766 =4754059056	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-33	OK
4511	+216022 =4754275078	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-33	OK
4512	+256180 =4754531258	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-33	OK
4513	+204885 =4754736143	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-33	OK
4535	+763320 =4791253397	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-32	OK
4536	+4751706 =4796005103	0x25	0x8E89BED6	ADV_DISCOVER_IND	6	0	0	14	0xB0B448D08783	02 01 04 04 FF 01 02 03	0x39FF06	-33	OK

Figure 16. Packet Sniffer

The TIDA-00690 sends out non-connectable advertisement packets that contain 8 bytes of data.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-00690.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00690.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-00690.

4.4 Altium Project

To download the Altium project files, see the design files at TIDA-00690.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00690.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-00690.

5 References

1. STEUTE Industrial Controls, Inc, *Wireless Digital Switches … New Control Possibilities*, White Paper (http://www.steutewireless.com/us/wireless/white-papers/wireless-digital-switches-new-control-possibilities.html)
2. Wikipedia, *Energy harvesting* (https://en.wikipedia.org/wiki/Energy_harvesting)
3. IDTechEX, *Electromagnetic induction in energy harvesting applications*, Research Articles (http://www.idtechex.com/research/articles/electromagnetic-induction-in-energy-harvesting-applications-00005834.asp)
4. CHERRY Electrical Products, *Energy Harvesting Technology* (http://cherryswitches.com/energy-harvesting-technology/)

6 About the Authors

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MATTHIEW CHEVRIER is a Systems Architect at Texas Instruments, where he is responsible for defining and developing reference design solutions for the industrial segment. Matthieu brings to this role his extensive experience in embedded system designs in both hardware (power management, mixed signal, and so on) and software (such as low level drivers, RTOS, and compilers). Matthieu earned his master of science in electrical engineering (MSEE) from Supélec, an Ivy League university in France. Matthieu holds patents from IPO, EPO, and USPTO.

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