Building a Light Switch with
Zigbee Green Power & Energy Harvesting

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Introduction

Power consumption in battery powered IoT devices has been a primary concern for the industry since its inception. The organizations behind the various wireless standards are playing an important role in helping meet consumer expectations across different technologies in this area, and Zigbee Green Power stands out as a great example of an effort to design wireless communication with energy harvesting in mind.

Working together, Silicon Labs and Arrow have developed an energy harvesting reference design based on Silicon Labs EFR32MG22 system-on-chip (SoC) that pairs a Zigbee Green Power light switch with energy harvesting power management. The MG22 is designed for use with the Zigbee protocol and is compact in size and boasts advanced security features, making it an ideal selection for ultra-low-power end devices.

The core element of this design is the energy harvesting generator. For this reference design, we've selected the Monostable Generator Module by ZF. This is a bi-directional switch generator, which means energy is generated when the switch is pushed down as well as when it's released. The illustration below shows the effect of the mechanical actuation of the switch, which has a magnet with two poles. Pushing the switch down creates a magnetic field through the core and back to the other pole. Then when the user releases the switch, the field changes and goes in the opposite direction through the core. Maxwell's Equation tells us that this changing magnetic field will produce a current, and this is the energy that we can harvest.

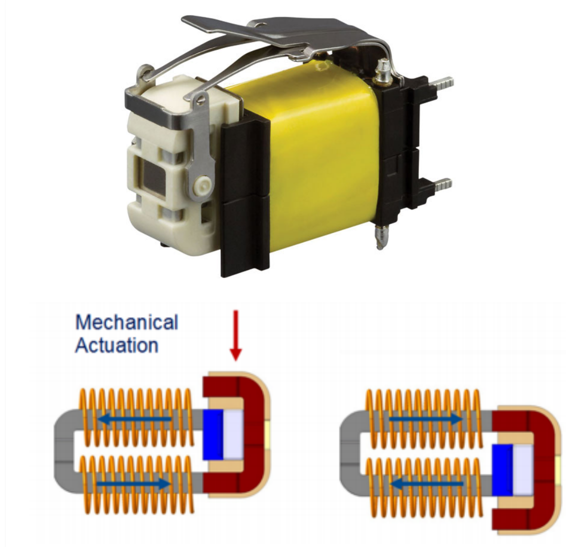


Figure 1: ZF Energy Harvesting Generator

Our end goal, of course, is to turn on a light without running a wire between the switch and the light fixture, and the diagram below provides a high-level overview of how we plan to accomplish this.

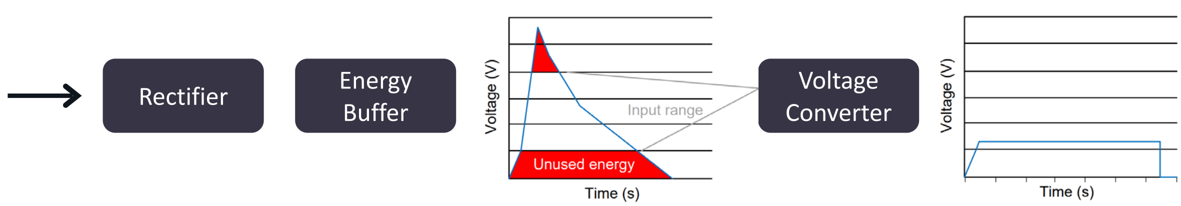


Figure 2: Design Considerations

The arrow depicts pressing or releasing the ZF generator, which produces an AC voltage. The voltage goes both above (positive) and below (negative) ground, but we need to use a diode to make the voltage positive. We can then feed the positive voltage into the energy buffer and in this case, we are using a capacitor. As shown in the illustration above, adding a diode creates a positive waveform. However, this is still not useful for our radio because we have a varying input voltage, so we need to add a DC to DC converter that produces a well-regulated 3.3 volts, which we can then use to power our radio. Now our system can take the harvested energy created by this mechanical energy and turn on the light.

Extracting the Maximum Amount of Energy

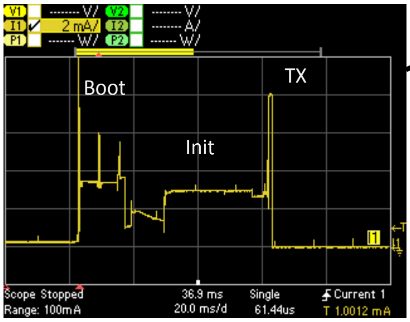
When designing an energy harvesting circuit, the challenge is to pull as much energy as possible, regardless of the load, to have a flexible design that can be reused across multiple systems. A dynamic system consists of a generator with a fixed output impedance. In theory, to maximize the energy generated, the source impedance needs to match the load. However, for a dynamic-behaving load this isn't possible. One alternative is to buffer the energy so it provides a constant supply to the active load. Then the challenge becomes extracting as much energy as possible from the generator without exposing a constant load. In the absence of a formal solution, we have to consider intuitive standpoints.

Another design consideration to keep in mind is that the generator will have two pulses: one positive and one negative. To maximize the energy extraction, we have to rectify the negative wave. There are two options for this: a full-wave rectification or voltage doubling. For this reference design, we've opted for a voltage double. This approach results in half the diode losses compared to a full-wave rectifier and results in overall better efficiency. With a full-wave rectifier, the energy left in the capacitor when the DC-to-DC reaches its undervoltage lockout (UVLO) is considered lost. With a voltage doubler, however, a second wave will charge the capacitor on top of its UVLO level and the energy will be fully utilized. By leaving the input capacitor of the DC-to-DC to charge for as long as possible, energy stops being extracted when the generator voltage goes below the voltage of the input capacitor. By enabling the DC-to-DC to start as soon as possible, the generator is operating as close as possible to its short-circuit operating point, which is also farther away from its maximum power point.

Finally, the input capacitor value, which is a function of the UVLO voltage, has been optimized through trial and error with the goal of maximizing the DC-to-DC run time. We can then feed power into the MG22 and communicate wirelessly using Zigbee Green Power to a wireless SDK or Green Power hub.

The chart below shows the performance results of this example. The SoC, which features 512 kB of flash and 32 kB of RAM, was modified to transmit only. This means it will wake up, boot, initialize, transmit, then go back to sleep. Our example utilized NVM3 and RTSL, and because this is a hardware design, there is no way to bypass this. As you can see, the total energy consumption at 3.3 V was about 587µJ.

- Test Parameters
  - MG22 (512KB / 32KB)
  - Based on Zigbee Green Power example
  - Modified for TX-only, one transmission
  - Uses NVM3
  - Uses Secure Element root boot
    - (no way to bypass this)



3.3V Measured					
Region	**Time (ms)**	**Current (mA)**	**Voltage (V)**	**Power (mW)**	**Energy (µJ)**
VSE / Root Boot	14.6	3.5	3.3	11.5	167.2
Startup, halinit()	12.5	1.6	3.3	5.3	66.0
emberGpdNvInit();	28.0	3.0	3.3	9.9	278.1
emberGpdRadioInit()	4.8	2.7	3.3	9.0	43.4
sendToggle(gpd);	1.6	6.2	3.3	20.5	32.7
All / Average	61.5	2.9	3.3	9.6	587.4

ZF Energy Harvesting Generator

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

Figure 3: MG22 and Green Power Energy Data

Comparing Common Battery Options for Sensor Development

Now, let's review which types of DC-to-DC converters can utilize the energy storing capacitor and create the well-regulated voltage required for the radio.

Silicon Labs offers energy-friendly power management ICs like the EFP0111. When starting this project, the EFP0111 was not yet available yet, instead the LTC3106 from Analog Device is used. This is a highly integrated, ultra-low voltage DC-to-DC converter with automatic power path management. At no load, the LTC3106 consumes very low quiescent current while creating 5 V of output from either input source. This is important for us because quiescent current is required to run the DC-to-DC converter. If the primary source is unavailable, the LTC3106 seamlessly switches to the backup power source, which allows us to charge a backup battery whenever there is an energy surplus.

There are some considerations to keep in mind when designing in a buck-boost converter. In the diagram below, our device has the power source coming in through the J4 headers. Power goes directly into the decoupling capacitors, which is necessary to oppose any unexpected changes in your input voltages from your power supply. When using decoupling capacitors, it's important to connect the capacitors between your power source and your ground, and you want to connect them as close as possible to your IC or they will be less effective. Note that Silicon Labs MCUs, wireless starter kits, and Simplicity Studio provide a powerful development and debug environment. To take advantage of these capabilities and features, we recommend including debugging and programing interface connectors into custom hardware design. In this design, we implemented a 10-pin Mini Simplicity connector. Another important note is that when designing in a debugger, some systems are capable of providing power, or input voltage, through the debug headers. It is possible that your DC-to-DC converter can be back powered, so it needs to be protected.

Below is an image of the final energy harvesting enclosure, which is shown only for reference here because it is not commercially available. It is visually appealing, which was one of our criteria, and the casing is constructed from laser-cured resin that will be painted with automotive-grade paint to simulate an off-tool color. The device has two buttons: an on/off button and one for commissioning and decommissioning.

Figure 4: Energy Harvesting Enclosure

PCB Design

When we first designed the PCB, it was a single piece that housed everything. However, given the design constraints set by the size of the enclosure and the mechanics of the energy harvesting switch, we decided to separate it into two boards.

In the figure below, the image on the left shows the energy harvesting generator. This PCB will lie vertically inside the wall of the enclosure, allowing for the actuation of the magnet inside the generator. This PCB connects to the second PCB and provides power. The image on the right shows the second, and primary, PCB. This PCB houses the buck-boost converter, debugger pins, rechargeable battery, and the headers for the radio board. You can also see on the second PCB that there are two contact pads for the buttons.

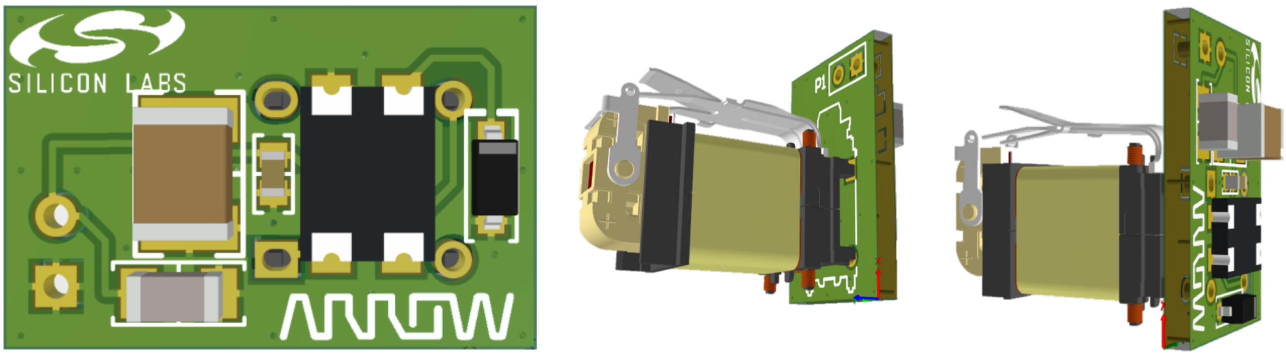


Figure 5: Harvester PCB

Our design contains two buttons, one large and one small. The smaller button is used for commissioning, and after it is commissioned can be repurposed as a Zigbee Green Power step-down command that can be used for dimming. Holding down the small button for three seconds will decommission the device. The large button can be used for on/off once the device has been commissioned to the Zigbee network. Each time the button is pressed, the radio wakes up from EM4 deep sleep mode and the device will wait five seconds before entering deep sleep mode again.

Options for Commissioning the Energy Harvester

Bidirectional commissioning between the switch and the hub is handled in four Zigbee Green Power commands. There are two options available for commissioning the device. If you're using an energy harvesting generator with a very small power budget, the process illustrated in the image below will be most effective. You'll press the small button a total of four times to complete each command while waiting one second between each button press. As you press each button, you engage the energy harvester and create more power for your device.

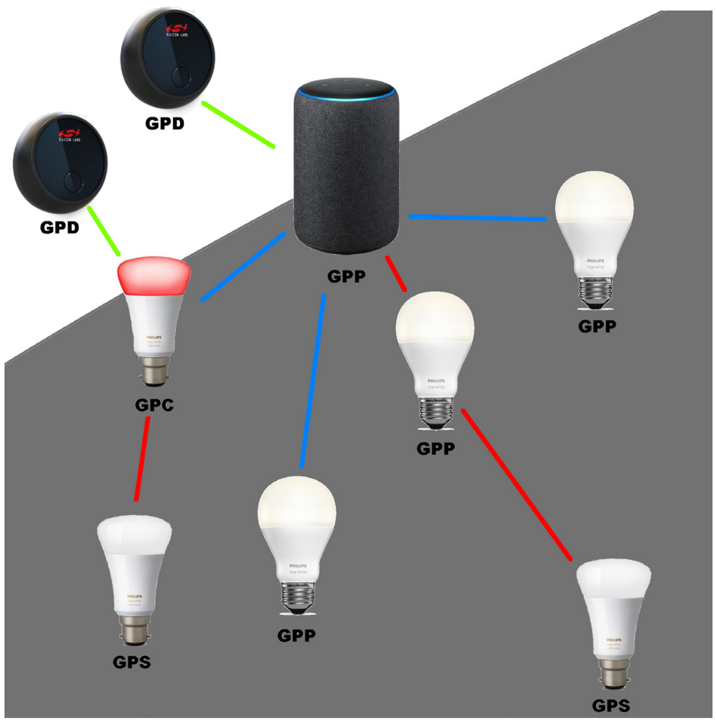


Figure 7: Energy Harvester GPD Commissioning – Option 1

The four commands in this process include:

1. Channel request to find the channel of the Zigbee network.
2. Channel request from the Zigbee Green Power device to the combo. The combo adds the additional Zigbee 3.0 commissioning payload to join the network.
3. Wake up the radio to receive the reply from the combo.
4. Acknowledgement

The second option has the same process, but the small button is pressed just once. This option uses time to send the four commands one second apart, but depending on network traffic, this could take longer and require more energy.

Conclusion

Powering IoT devices is an energy-intensive endeavor and innovating on new ways to power our devices without batteries will simplify development and contribute to a cleaner environment. For example, harnessing the energy required to make an LED blink just once is enough to transmit multiple RF signals. Low-power silicon designs coupled with networks optimized for low-power applications will set the stage for a new era of power management and translate into dramatic cost and waste reduction for manufacturers and consumers. For more information on Zigbee Green Power, check out our Knowledge Base article here. If you're planning an Energy harvesting switch based on this reference design, we'd love to hear about it.

Silicon Labs EFRMG22 SoC

The MG22 family of SoCs are optimized Zigbee solutions bringing industry-leading energy-efficiency to IoT applications include smart home sensors, lighting controls, and building and industrial automation.

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