SCTE · ISBE CABLE-TEC EXPO 2019
NEW ORLEANS, LA
SEPT. 30-OCT. 3

2019 Fall Technical Forum
SCTE·ISBE • NCTA • CABLELABS

IoT Device Energy Harvesting Technologies and Implementations

A Technical Paper prepared for SCTE/ISBE by

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1. Introduction

The proliferation of wireless home security and automation sensors and devices, i.e., the so-called Internet of Things (IoT), has advanced the need for improvements to battery life. The cable industry has deployed IoT sensor solutions for many years (in home security devices such as motion sensors, for example), but it needs to reduce costly service calls for replacing batteries and to work towards addressing global environmental concerns regarding the disposal of spent batteries.

Currently, the capacities of inexpensive chemical batteries are reaching their physical limits, and the concurrent drive to create ever-smaller devices calls for further innovations to extend battery-powered sensor life. Chief among these is energy harvesting. This paper focuses on promising energy harvesting methods and solutions that may be applied to IoT devices. Business and consumer drivers for improved efficiency sensor-powering solutions are also discussed.

Sample test results examining both performance and economic impacts are evaluated. Of particular importance is an assessment of user and system operator experiences, the perspectives of time and cost savings. Finally, recommendations are proposed that identify implementation opportunities for Multiple System Operators (MSOs).

2. Sources of Power

A variety of energy harvesting sources will be discussed in this paper, such as wind, rain, heat, cold, vibration, water flow in pipes, ocean currents, induction (temperature/electrical), motion, sunlight, and artificial light. Some of these energy sources can provide a direct power input, while others, depending on the application, can be utilized for target implementations. For example, solar energy can be converted directly into power to be used for long-term functions, such as a solar-powered light, or to top off batteries such as those used in solar calculators. Separately, the water flow in home plumbing pipes can be used to power a sensor (to send a status message) to indicate that water flow is present.

3. Transferring Environmental Energy to Power IoT Devices

There are three modes of providing harvested energy to a device:

- Hybrid Mode
- Assist Mode
- Standalone Mode

These modes are described more fully in the subsections that follow.

3.1. Hybrid Mode (Ability to charge a battery)

Hybrid mode extends battery life and, in some cases, allows for a battery of a smaller form factor to be used to provide for the same design functionality and expected battery life as a larger battery. The device operates either on energy harvested in real time or on harvested energy that is stored, depending on the amount of energy available for harvesting.

Using harvested energy for charging a battery has some drawbacks. First, there is a loss of energy to implement a step-up or step-down circuit; the device requires the addition of a rechargeable battery and a charging circuit (an example is shown in Figure 1, below); and power for the device is dependent upon favorable environmental conditions (e.g., solar cells typically yield the most energy in sunny climates).

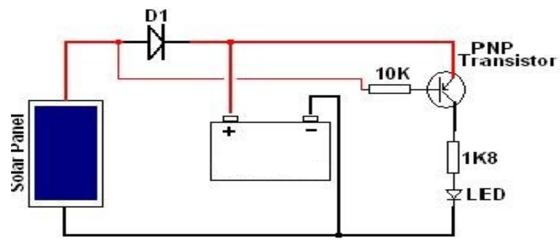

Figure 1 – Charging circuit and battery for storing energy from a solar panel

3.2. Assist Mode (Ability to Store Limited Energy)

Assist mode is an energy-efficient method where a smart circuit utilizes environmental energy. Such energy may be very low power or have infrequent availability, such as a solar cell utilized indoors that can assist with device function or "store" energy for future use in a capacitor or supercapacitor (i.e., a capacitor with extremely high capacity and low leakage loss over time).

It is challenging to use coin cell batteries in an assist-mode configuration since they have high internal resistance which causes a voltage drop during high-current demand, e.g., during transmissions to and from IoT devices. IoT SoCs (Systems on a Chip) are rated for a "cutoff voltage," i.e., the voltage at which the device will cease to operate. The addition of a supercapacitor significantly reduces the voltage drop at high-demand periods, consequently raising the cutoff voltage of the device and thereby extending the battery life.

Assist mode can also be implemented with the addition of a small solar cell utilized to "top off" a battery for extremely low cost, for example, in basic handheld calculators or wearable devices where motion is converted to supplemental power for a device.

Figure 2 – Example of a supercapacitor

3.3. Standalone Mode (Operated by harvested energy only)

In standalone mode, only the harvested external energy powers the device. Examples of devices using this method are IoT devices without internal energy storage, such as low-cost Zigbee light switches (mechanical-to-piezoelectric) and solar-only powered IoT devices. Figure 3, below, shows a solar-only powered calculator which works well in bright light, but is challenged to operate effectively in low-light conditions.

Figure 3 – Solar-powered calculator

4. Device/Sensor Design Considerations

Circuits, including SoCs with wireless capability in IoT designs, are utilizing less power over time for increased functionality. Sleep currents in SoCs and microcontroller units (MCUs) are now operating in the nanoamps range, and the operational voltage required is decreasing over time; it is currently as low as around 1.7 V for contemporary SoCs. If a voltage requirement of less than 1.5 V is accomplished in the future, SoC operational voltage requirements would line up with commonly available 1.5 V batteries. Utilizing 1.5 V batteries would be of benefit since devices would generally not require boost circuits or batteries in series to support a SoC's operational voltage requirements.

As the illustration below indicates, efficiency of energy harvesting technologies is increasing while the wattage required for the electronics is decreasing, so we are likely to see smaller and more energy-efficient devices continue to develop.

Energy Harvesting Technologies Wattage   Electronic Circuit Wattage

The third leg of the stool for the above illustration is the most challenging for designers to implement: crafting software that goes beyond basic functionality to achieve a highly energy-efficient device. For example, turning off circuits when they're not in use and decreasing the CPU cycles for targeted functions, if supported by the SoC, decreases energy use and hence extends battery life.

5. Device/Sensor Examples

Device/sensor energy harvesting can be one of three types: conductive, mechanical, or radiant/electromagnetic energy. Conductive energy harvesting can be achieved through a temperature differential between two surfaces. Mechanical energy harvesting is achieved through motion/vibration. Radiant energy can come from the Sun as solar energy and from the Earth's natural electromagnetic field as Schumann resonances. Unfortunately, the energy harvested via Schumann resonances is impractical for sensors since the amount of energy collected would be very small and would require a very large antenna to collect.

A push-button Zigbee wall switch (Figure 4) utilizes mechanical energy, through the motion of pushing a switch, to generate enough energy to send out a Zigbee message. This technology is excellent for sending a simple one-way message. However, without having the power to receive an acknowledgement or retry message without another mechanical action limits the use of this type of harvesting method.

Figure 4 – Zigbee wall switch

6. Mechanical Energy Harvesting

Mechanical energy can be harvested from motion or vibration and converted into electrical energy for devices/sensors. Utilizing Peltier technology, applied vibration provides electrical power, such as in a Peltier device mounted to a vibrating motor. For example, door sensors can utilize the mechanical motion of the door opening and closing to power themselves. In the "shake flashlight" (Figure 5), magnets and wire coils combine with mechanical motion to induce a current that generates enough power to light an LED.

Figure 5 – Example of a shake flashlight

7. Solar Cell Energy Harvesting

Solar cell devices are ideal for outdoor areas where sunlight is prevalent for approximately 12 hours a day. Solar cells can also be utilized indoors to provide supplemental power to a device. Obviously, however, there are limitations for indoor use (indoor power is generally 1/1000 that of outdoor power), and efficiency is highly dependent on the application and placement.

For IoT devices, two-way and one-way communications may be utilized for applications. For simple one-way communicating devices with short messages, energy harvesting is ideal in standalone mode where it is the sole source of power, such as with the Zigbee light switch. For two-way communications, especially for security systems where there is frequent messaging, energy harvesting is more applicable as a supplemental energy source.

Most IoT devices tend to be black, dark gray, white, or off-white in color. Adding an energy harvesting solution such as a solar cell may change the aesthetics of the device, as solar cells are usually copper or black in tone with an overlaying metal grid. IoT device manufacturers strive to integrate the energy harvesting technology into the device with the best aesthetics possible. The remote control with a solar cell (Figure 6) uses ambient light in the home, when available, to provide supplemental power and charge the battery. With this approach, either the life of the remote control's primary batteries can be extended or the number of primary batteries in a remote control can be reduced. The addition of a non-replaceable rechargeable battery or a supercapacitor storage mechanism is typically utilized to accomplish the aforementioned applications. The customer experience would thereby be enhanced by the extension of the battery replacement period and/or the overall reduced cost of primary cell replacement.

Figure 6 – Remote control with solar cell

8. Temperature Transfer Energy Harvesting

The concept of harvesting heat energy is used in the flashlight shown in Figure 7. This device uses Peltier tiles to convert heat from the hand holding the flashlight to electricity to power the light. Peltier tiles generate electricity when the temperature differential of its top and bottom layers is approximately 5° C.

Figure 7 – Flashlight with Peltier tiles

9. RF Energy Harvesting

Harvesting RF-transmitted energy depends on the level of transmissions and the conversion of RF energy to actual utilized power, such as paralleling the antenna and energy harvesting from the RF power provided by the antenna on transmission. Directing such power to a capacitor to be utilized for future transmission or other device is one harvesting method.

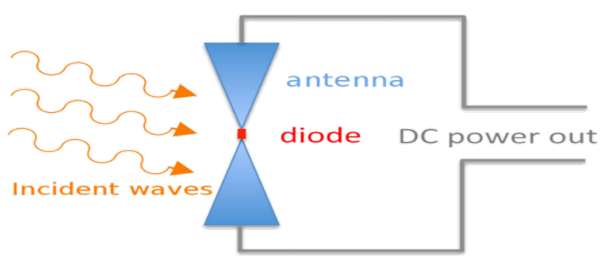

Figure 8 – Harvesting RF energy to generate DC power

10. Advanced Energy Harvesting

Advanced energy harvesting technologies may be cost- and implementation-challenged, but they are noted here for their promising potential. The examples MEMS pyroelectric capacitors and nano-antennas are summarized in the subsections below.

10.1. MEMS Pyroelectric Capacitor

A MEMS (microelectromechanical systems) pyroelectric capacitor is a technology for harvesting residual heat to power devices/peripherals, such as a USB port or HVAC system vent position.

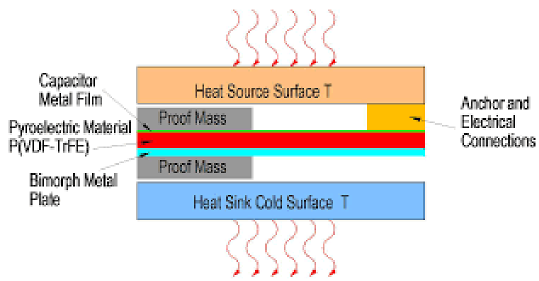

Figure 9 – MEMS Pyroelectric Capacitor Concept

10.2. Nano-Antennas (Nantennas) for Solar Energy Harvesting

Nano-antennas achieve close to 90% efficiency compared to 10-20% for silicone-based solar cell energy harvesting. Using silver in nantennas produces higher efficiency and allows fine-tuning the dipole dimensions. Below are two examples of nantennas (Figure 10).

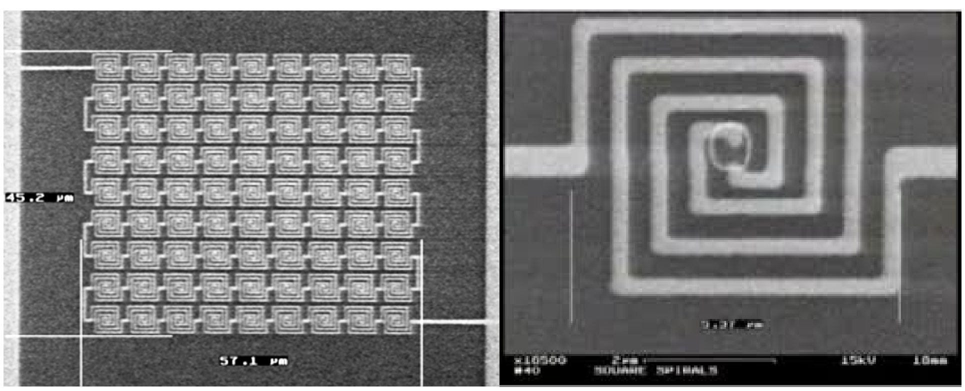

Figure 10 – Two Examples of Nano-Antennas

11. Summary

Battery technology capacities per form factor for IoT devices have stabilized somewhat for now. The IoT battery-life design challenge must be met with a coordinated multi-pronged approach that matches the design choice with the environmental energy available for harvesting. Electronics engineers need to choose low-energy electronics/designs and, even more importantly, craft smart software for energy conversation wherever possible.

Improving IoT battery life reduces overall battery change-out costs, resulting in fewer service calls (thus reducing operator cost) and increased customer satisfaction. Additionally, the extension of primary cell battery life or the reduction in the number of primary cells utilizing energy harvesting furthers the extensive opportunities for a "green initiative" for the cable industry.