Energy Harvesting

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Contents

1   Introduction

Small electronic devices are increasingly present everywhere around us. With their ubiquity and ever decreasing size and power consumption, connecting each of them to the power grid becomes impractical.

The traditional solution is to use batteries, but they come with their own set of problems. Replacing them can be expensive, especially in hard-to-reach places. A much better option would be if the device had a power source of its own, removing its dependence on the power grid and drastically reducing the maintanace cost [1].

The practice of drawing small amounts of electricity from the device's immediate surrounding is called Energy harvesting (EH).

2   Use-cases

2.1   Sensors

A very common use for energy harvesting systems are nodes in Wireless sensor networks (WSNs) [2, 3]. Such a network can contain a large number of independent nodes, so it would be difficult to connect each node to the power grid with wires. The sensors themselves usually consume very small amounts of power, so they are ideal applications for Energy harvesting methods. A block diagram of a generic sensor node can be seen in Figure 1.

The applications for WSNs include [4]:

- Weather stations

- Air and water pollution measuring

- Fire detection

- Industrial machine health monitoring

- Structural monitoring in buildings

- Intelligent buildings [3]

Most of these applications require the nodes to be outside or in other areas where a direct connection to the grid would be difficult. On the other hand, they can still be close enough to the central node so they can transmit the measurements over a wireless connection with their own harvested power.

Another important characteristic of sensor nodes is their power consumption profile. Often they will be idle for a long time (from minutes to days), and perform measurements in a relatively short time. The transmission of data can be even more infrequent, depending on whether the data has to be available immediately or not. In any case, sensor nodes consume very little current in the idle time period, with short bursts of consumption at regular intervals. An example of such consumption profile is in Figure 2.

The average power consumption depends mostly on the duty cycle. If the measurement and especially the transmission of data does not have to be very frequent, the average consumption can be made very low. The consumption during the inactive time is often of the order of a few μW [6]. For example, electrical characteristic of an automatic radiator valve which take a measurement every hour are listed in Table 1. This system draws an average power of 1 mW and would normally need it batteries changes at least once a year [2].

2.2   Consumer electronics

Many popular electronic devices, including TV remote controls, digital watches, portable music players and mobile phones, have power consumption low enough to be powered or at least assisted by EH. Although their batteries can last a very long time, they can run out unexpectedly and cause a severe inconvenience.
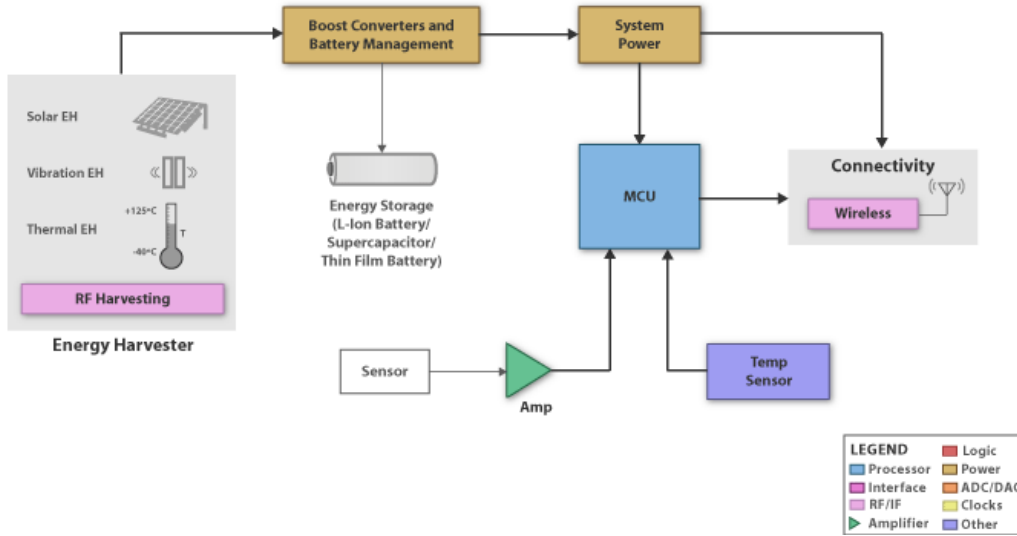
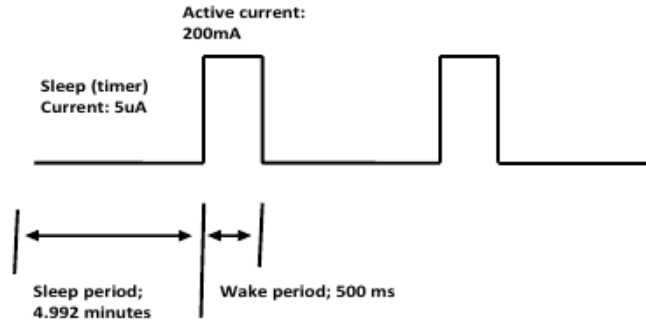Figure 1: Block diagram of an EH-powered wireless sensor node [5]

Figure 2: An example of a WSN current consumption profile [3]

Solar cells on pocket calculators are very common and well-known, but so far their use has not spread to other electronic devices. There are, however, studies and working examples of remote controls for television and cars using a piezoelectric generator powered by the pressing force of our fingers, so this might change in the near future.

2.3 Spacecraft

The impracticality of a grid connection or battery replacements is most evident in space. Satellites in orbit around Earth or travelling close to the Sun carry arrays of solar cells, harvesting energy from the Sun's radiation to power their systems.

Deep-space probes, on the other hand, often fly too far from the Sun for solar energy to be a viable solution. Such probes are equipped with Radioisotope Thermoelectric Generators (RTGs) which convert heat from a slow radioactive decay to electricity. The farthest man-made object from Earth, Voyager 1, has been succesfully operating on RTG power for nearly 35 years, and is projected to do so for at least 15 more.

3 Important properties

When choosing the EH method to use in a project, the most important factor is the available types of energy in the device's surroundings. These types will be explained in more detail in the following chapters. However, we must also consider the electrical characteristics of the chosen product, as

Parameter	Value
Supply Voltage	2.7 - 3.3V
Working current	60 mA
Sleeping current	10 μA
Working duration	20 seconds/hour
Working duration	3579 seconds/hour

Table 1: Electrical characteristics of an automated radiator valve

Figure 3: A solar-powered calculator by Casio (left) and a GPS satellite with solar panels (right)

well as its cost and physical size.

Most EH devices are far from being an ideal power source. Therefore, we must carefully consider their electric properties before connecting them to our load.

3.1 Source resistance

According to Thevenin's theorem, any combination of ideal voltage sources, current sources, and resistors with two terminals is electrically equivalent to a single voltage source in series with a single resistor. This simplified representation serves as a good model for most power supplies and batteries. The resistor represents the source resistance or internal resistance of the power source.

A source with internal resistance R and current I draws power equal to I^2R. This power is wasted, reducing the already limited available energy, so we usually want power sources with low source resistance.

Source resistance is also very important in power transfer. The most power is transferred when the source resistance is equal to the resistance of the load. The source resistance can be very different than the resistance of our load, and can even change with time. Fortunately, DC-DC converters exist which are able to increase or decrease both the voltage and resistance, providing matched resistances on both ends.

3.2 Open-circuit voltage and short-circuit current

Open-circuit voltage (V_{OC})is the voltage between both terminals of the power source when no current is running through it. This is equivalent to loading it with an infinite-resistance load. This is the maximum voltage the source can produce; if a nonzero current is running, the source resistance will cause a voltage drop inside the source, causing a drop in the output voltage.

Short-circuit current (I_{SC}) is the opposite to open-circuit voltage. It specifies how much current the source is capable of generating under a load with zero resistance. In this case, the whole voltage

drop happens inside the source, driving the output voltage to zero.

In both of these extreme cases, the power output drops to zero. However, the characteristics are important because they are very easy to measure and compare. Sometimes these two pieces of information can be enough to make an informed choice of a power supply [6].

3.3 $I(V)$ curve and power curve

The current-voltage characteristic, also known as the $I(V)$ curve, shows how much current the generator can output at voltage V. Because all EH sources have limited power, current will always drop if we put a load with nonzero resistance on the source. Similarly, a low-resistance load will increase the voltage drop inside the source, causing the output voltage to decrease.

A power curve is the relationshpi between the output power of the source and the load voltage. The electical power output is given by $P = V \cdot I$, so the current curve is simply the $I(V)$ curve multiplied by the voltage V. However, it is often the most important one as we wish to have the power source operate at its maximum power output.

3.4 Efficiency

When the available power is low, it is important to convert as much of it to electricity as possible. The ratio of electrical energy produced versus the solar, mechanical or thermal energy consumed is given by the efficiency. Efficiencies of EH sources vary greatly depending on their conversion method and size. In general, they provide lower efficiencies than larger power sources.

4 Photovoltaic cells

The best known method of generating electricity from the environment on a small scale are photovoltaic cells. In most environments, they provide the highest power output of all EH devices.

4.1 Theory

The solar cells work by using the photovoltaic effect to create electron-hole pairs in a two-layer semiconductor by exciting the electrons to the conduction band. Once in the conduction band, the electron moves to the n-doped side with lower potential without crossing the gap. The flow of electrons from one side of the cell to the other creates voltage between the two metal contacts [7]. A diagram of potential levels and the electron's path can be seen in Figure 4.

4.2 Characteristics

Modern photovoltaic cells can reach efficiencies up to 30%. However, it is possible to use mirrors or lenses to concentrate more sunlight onto the cell, effectively raising it efficiency up to 45%. This is useful because the concentrating optics are usually cheaper than solar cells themselves. On the other hand, such concentrators often require a system for tracking the sun, resulting in a more complicated solution, and are better suited for large-scale operations than for energy harvesting devices.

Unlike other power sources, a photovoltaic cell can be modelled as an ideal current source connected in parallel with a diode. The open-circuit voltage is then equal to the diode's forward voltage, while the short-circuit current is the output of the model's source generator. A typical solar cell has a V_{OC} of around half a volt. The short-circuit current and with it the power output is very dependant on the light conditions and cell size. Because of the voltage of a sigle photovoltaic cell, they are often connected in series. Alternatively, power can be drawn from a single larger cell with the help of a converter [1].

The downside of solar generators is the constant changing of their power output. Fortunately, there are several methods to work around this shortcoming. One way to is to use supercapacitors [3] to store the produced energy. Even so, with variable weather conditions, the cell is not always operating with its peak efficiency. The shift in its optimal power point can be seen in Figure 5.
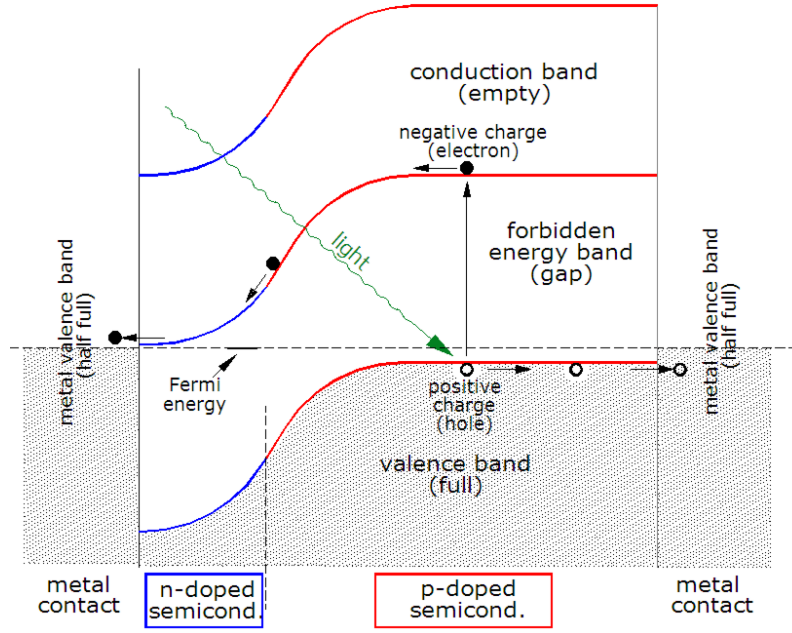
Figure 4: Band diagram of the semiconductor inside a solar cell [7]

It is possible to offset this by using a system that dynamically adjusts the cell voltage to find the maximum power point [8].
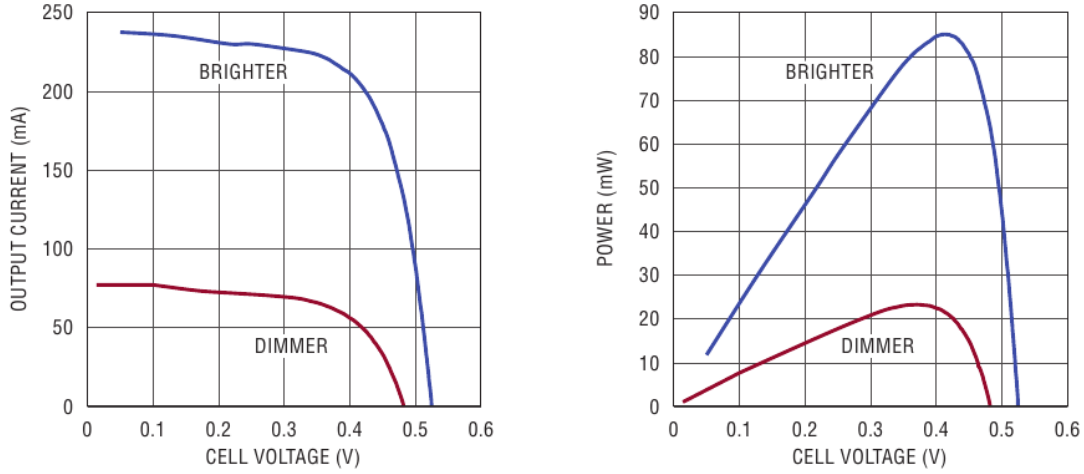

Figure 5: Typical $I(V)$ and power curve of a 2x1 inch (13 cm^2) polycrystalline cell [1]

4.3 Light conditions

Ambient light conditions are very important in determining the power output of photovoltaic cells. Besides only producing power during the daylight hours, solar cells are severely hindered by bad weather. In places with long periods of low light, such as rainy seasons or high lattitudes, large batteries are needed for energy storage.

The situation is different if the cells are located inside a building. Indoors lighting is on average 400 less intense than the irradiation by the Sun, resulting in correspondingly lower power outputs. However, the energy input is much more constant, especially the low-light periods are shorter and

predictible. Despite the lower peak intensity, solar cells are useful even in indoors environments. Because most such devices can be made with power cords instead, the benefits of EH are smaller there, but may still be significant with small and/or mobile devices.

5 Thermoelectric generator

Another source of energy in the environment is a temperature gradient. This method has become very popular in the recent years, mostly due to their reliability and lower cost than photovoltaics.

5.1 Theory

Using the Seebeck effect, it is possible to convert this difference in temperatures into electricity. The Seebeck effect is the converse of the better-known Peltier effect, so the same elements can be used for either thermoelectric cooling or power generation.

Thermoelectric generators (TEGs) are typically made from a series of alternating N-doped and P-doped semiconductors, sandwiched between two ceramic plates [6]. A schematic of their design can be seen in Figure 6.
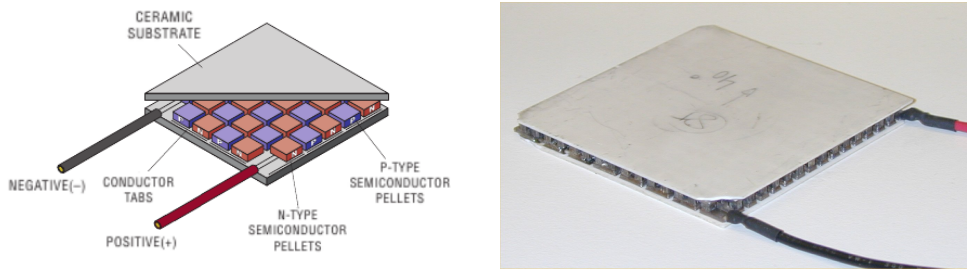

Figure 6: A schematic (left) and a photo (right) of a TEG element [6, 9]

Due to their simple design and the possibility to re-use existing Peltier coolers, TEG can be much cheaper than other EH devices.

5.2 Characteristics

Both the output voltage and the source resistance are directly proportional to the number of couples in the series, so it is important to use the right size of the generator to ensure a high enough voltage while still keeping the resistance low [6]. Characteristics of `TEC1-12709`, a common thermoelectric element which costs $7.25, are given in Table 2. Mounted on a radiator with temperature 30 K higher than that of the surrounding air, four such generators stacked in layers are capable of producing a maximum of 60 mW at 700 mV [2].

Parameter	Value
Dimensions	30 x 34 x 3.2 mm
Maximum ΔT	77 K
Number of couples	127
Device resistance	3.78 Ω

Table 2: Physical properties of a TEG

6 Piezoelectric generators

The third most common form of EH is generating power from the energy of motion. Vibrations are present especially in the vicinity of working machinery, but energy can also be produced from human activities, such as walking [10].

6.1 Theory

Certain clystalline materials with asymmetric unit cells polarize themselves when an external force is applied. This phenomenon is called the Piezoelectric effect. The best-known material to exhibit piezoelectric behavior is lead zirconate titanate (PZT), a ceramic with the formula $Pb[Zr_xTi_{1-x}]O_3$, $0 \leq x \leq 1$.

Like the thermoelectric effect, the piezoelectric effect also has a direct converse, where a voltage applied to the material causes it to deform. Because of this, the same elements can be used as actuators, capable of very precise positioning due to the high voltages required for small mechanical deformations.

In piezoelectric materials, the dielectric response $D = \varepsilon E$ and Hooke's law $S = sT$ are coupled [11].

$$\mathbf{S} = s\mathbf{T} + d^t\mathbf{E} \tag{1}$$
$$\mathbf{D} = d\mathbf{T} + \varepsilon\mathbf{E} \tag{2}$$

Strain $\mathbf{S}$ and stress $\mathbf{T}$ are rank-2 tensors, but because they are always symmetric, they have only six free parameters and can be written as vectors with 6 components. Compliance s, permitivity ε and piezoelectric matrix d can now be written as rank-2 tensors. The first equation describes the converse piezoelectric effect (mechanic deformation under applied voltage) while the second describes the direct piezoelectric effect (polarization under applied stress).

The values of d are different for every material. For tetragonal and hexagonal crystals, only five out of 15 coefficients in the matrix are nonzero [11].
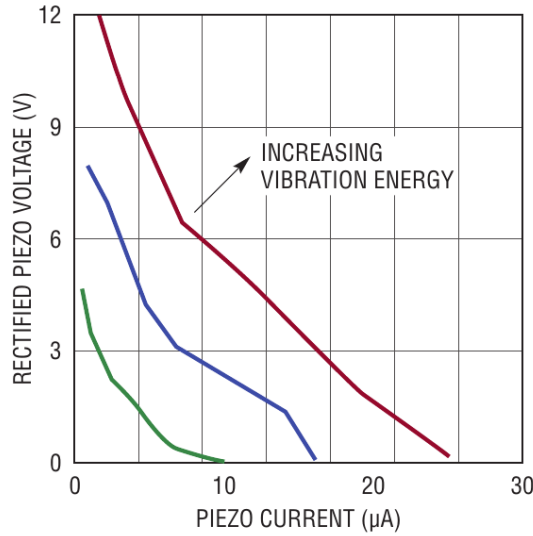
6.2 Characteristics

Figure 7: Typical piezoelectric load lines [12]

Unlike other EH methods, piezoelectric elements often produce relatively high voltages, so a converter is needed to decrease the voltage. Both open-circuit voltage and short-circuit current increase with the available vibration energy [12]. Figure 7 shows load lines for Piezo Systems T220-A4-503X with a wholesale price of $70 per piece. We can observe that the lines are close to hyperbolas, so power output does not depend on the voltage applied, only on the vibration energy present. This particular element can function both as an energy harvester or an actuator and is rated for voltages up to ± 180 V. In typical vibration energy harvesting applications, the output voltage is much lower, but still high enough to require a specialized power supply.

Using a smaller device, researchers were able to produce produce an average power of over 8 mW from a PZT-based piezoelectric mounted inside a shoe. This was enough to continuously power a short range radio frequency emitter [10].

7   Power management

As mentioned above, electrical power from EH generators can be very sporadic, and so can be the required load. Therefore, additional electronics are require to turn the energy source into a useful power supply.

The first step is to ensure the maximum power transfer between the source and load. Differences in output voltage and resistance force us to use DC-DC converters. These converters can easily reach efficiencies of over 95%, so they do not cause an excessive power loss. A major part of the power management system is also the storage and retrieval of energy in a separate container. Depending on the storage method, a suitable charging mechanism must be included.

Converters for different energy sources, such as those made by Linear Technology, are available in bulk at $3-$4 per piece. Battery charge controllers are also widely available at low prices, around $2 per piece. In total, the cost of the power management system is only a small part of the total cost of the power source, the majority being the energy harvester itself [13].

8   Energy storage

In most cases, energy is stored either in batteries or ultracapacitors. Ultracapacitors, also known as Electric double-layer capacitors, are the newer technology, and are used where higher power density (as opposed to energy density) is required. En example of such a system is a wireless sensor node with its short spike of power consumption during transmission of data [3]. Other advantages of supercapacitors include long life with no danger of overcharging or over-discharging and low internal resistance, while their main disadvantages are lower energy density and high self-discharge rate [14].
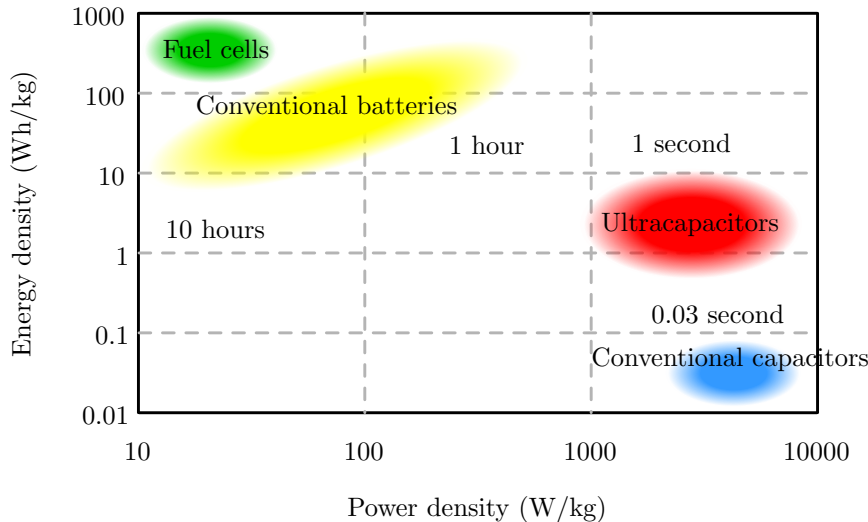

Figure 8: Comparison of energy storage options [14]

Energy storage methods other than batteries and ultracapacitors are not widely used in energy harvesting. Fuel cells could be used in place of batteries, due to their high energy density and long life, but they are more complex and difficult to make in small sizes. They also require an external fuel source, negating the benefit of reduced size required to store the same amount of energy.

Conventional capacitors, on the other hand, have very low energy densities and offer virtually no advantage over ultracapacitors.

Obviously, the choice of the energy storage method depends on the applications. For a solar-powered calculator, batteries have an advantage because of their lower leakage, and the device never requires a high power output. It is also possible to use both, an ultracapacitor for sudden spikes and a battery for long-term energy storage.

9 Succesful implementations

9.1 Building automation

The EnOcean Alliance is a consortium of companies providing a building automation system with an open, interoperable standard for energy harvesting [15]. Its members offer wireless sensors, switches and controllers, capable of managing a building's lighting, heat, ventilation and air conditioning systems. Wireless communication is done in the 315Mhz and 868MHz bands, thus requiring less power than 2,4GHz used by the `IEEE 802.11` standards, traditionally used for wireless computer networks. An example wireless network with EH-powered sensors and grid-connected central nodes and routers is in Figure 9.
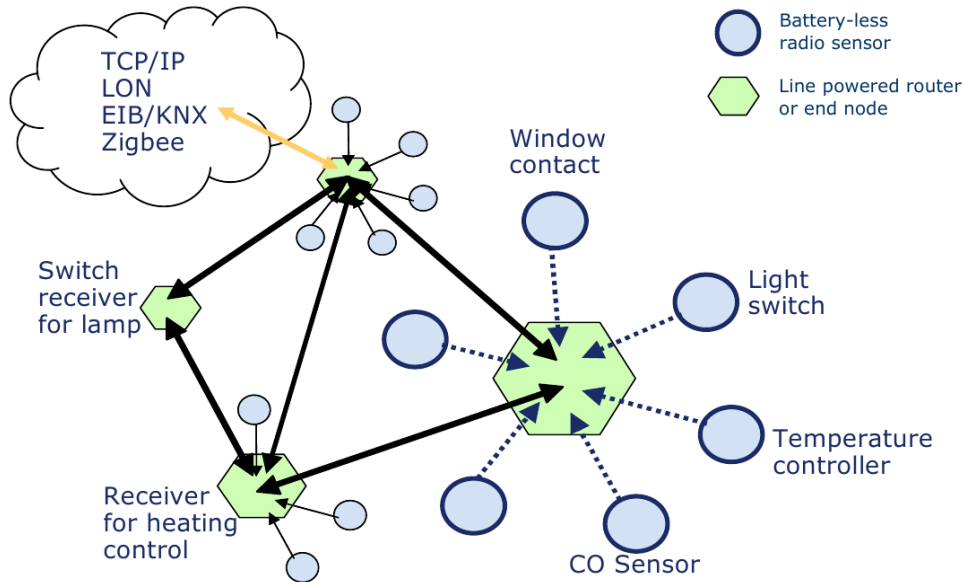

Figure 9: A wireless sensor network based on the EnOcean standard [15]

A competing group of companies constitute the ZigBee Alliance. Aside from building automation, they also offer health care and remote control applications. However, they have only recently began adopting EH, with the first batteryless wireless switch presented by Schneider Electric in 2009 [16]. As we can see in Figure 9, the two standards are compatible and can be linked via a gateway device.

9.2 Phone and laptop chargers

Several companies offer solar-powered chargers for phone and laptop batteries. In these cases, the goal is often not to power the devices solely through EH, but mainly to extend battery life.

A typical modern laptop computer under light load consumes an average power of around 20 watts. This is far beyond the range of small energy harvesting solutions, so the solar cells have to be very large, making them both more expensive and less portable. Solar laptop charges, powerful enough to provide at least 10 watts in optimal conditions, thus require almost half a square meter of

surface area and can cost over $500. However, smaller and cheaper power sources can still provide a significant increase in battery life, especially for smaller, less power-consuming laptops [17].

Mobile phones, on the other hand, require much less power. A phone spends most of the time in a sleeping state, in which it consumes less than 100 milliwatts. Hence the chargers can be the size of the phone itself and cost around $30. Due to their small size, they cause no additional burden when being carried around, proving true energy harvesting devices [18].

10 Conclusion

Energy harvesting (EH) is becoming increasingly viable as a power source for small electronic devices. Because of their remote location or simply due to their small size and large numbers, it may become impractical or even impossible to connect such devices to the power grid or to supply them with batteries. Hence, an included small power source can drastically simplify the device installation and reduce its maintanace costs.

We have seen three different methods for drawing power from the device surrounding, provided we have a source of light, heat or motion. The choice of a suitable method obviously depends on the device and the environment in which it is meant to be used. There are other possible approaches, but these three are the most popular at this time.

Because the energy source might not be present at all times, as is the case with photovoltaic placed outdoors, we also need to store the harvested energy. In this field, ultracapacitors are seeing rapid development and have become an alternative to more traditional batteries. Many wireless devices have a short duty cycle, during which the higher power output of capacitors is an important advantage, while their average power consumption is still very low.

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