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Article

Bluetooth Low Energy Beacon Powered by the Temperature Difference

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Abstract: Bluetooth low energy beacons are active transmitters that send a radio signal at set intervals. Most beacons are powered by small batteries. The problem with systems based on such devices is the need to periodically replace the chemical cells. This is especially tedious when a large number of the beacons is used. The maintenance of such a system causes several serious problems related to the high cost of new batteries and their replacement, time-consuming service and environmental pollution. A solution to these problems is to use beacons with a power supply supported by photovoltaic panels. Their obvious drawback is the need to place them in good lighting conditions. To overcome this disadvantage, the use of a power source that gathers energy due to the Peltier effect is proposed in this paper. Since the temperature difference between two surfaces can be found in almost every environment, the authors analyzed the efficiency of this kind of energy source in the context of powering the beacons. In order to justify the idea, a multitude of measurements and simulations was performed. The power supply demand of the beacon was measured in various modes of operation. The Peltier module was examined at different loads and various temperature differences. On the basis of the gathered data, the energy conditioning system was defined for a given temperature difference sufficient to power the beacon. Finally, the model of the proposed device was developed. The elaborated solution eliminates the need for batteries and makes the beacon maintenance-free.

Keywords: beacon; Peltier module; energy harvesting; Bluetooth

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1. Introduction

Beacons are devices that communicate with Bluetooth low energy (BLE) technology in the 2.4 GHz band. Their purpose is to send a signal of a certain power in set intervals, and pairing with the devices receiving this signal is not required. In addition, the beacons can be equipped with sensors that send measurement data regarding environmental parameters, such as pressure, temperature, acceleration and others [1]. This information can be received by any devices equipped with a Bluetooth module, for example mobile phones [2]. The main use of beacons is to broadcast information related to the place where they are attached [3]. One of the basic examples is an advertising application in which the transmitter is placed next to a shop window and broadcasts information about current promotions, thus encouraging customers to make purchases [4]. In addition, these devices can be used in many different navigation systems. For example, objects can recognize their position by measuring the strength of the signals received from several beacons located at different points of space [5]. When the transmitters are deployed in a building (office, school, university, etc.), they can be used to determine the position of a user equipped with a smartphone and an appropriate application containing a map of rooms [6]. The collected information on building occupancy can be used in artificial intelligence to manage various socio-economic processes [7,8]. The beacons can also be placed on moving objects for radio identification, tracking and remote monitoring of parameters [1]. Based on the strength of the signal sent by the beacon, the distance from the marked object to the receiver can be determined. An example is a transmitter in the form of a pendant attached to keys or other moving items [9]. Using a smartphone or other mobile device with an appropriate application, the user is able to determine the position of the lost object. It is also possible to track the beacon placed on a vehicle by using a network of receivers [10]. Smart grids with beacon nodes are also becoming more commonly used in smart homes [11,12].

The BLE beacons are the active transmitters, so they require their own power source to work. Most often, batteries or accumulators are used for this purpose [13]. Since there is no need to run power cables, the beacons can be freely located within the operating areas of applications. On the contrary, the need to periodically replace the batteries is the main disadvantage of the solution because it involves high costs related to the production, maintenance and utilization of the batteries. Although a lot of work has been devoted to reducing the energy consumption in beacons [14], the used batteries still have to be subjected to tedious disposal [15]. This problem is especially visible at the Rzeszów University of Technology (Poland), where a navigation system for disabled people based on 2000 beacons located inside the university buildings has been implemented (https://uczelniadostepna.prz.edu.pl (accessed on 29 January 2023)). The transmitters are set to send signals with a power of 0 dBm in a time interval of 1 s. They are powered by batteries that have to be replaced every year. Given the large number of devices, system maintenance is time consuming, expensive and generates waste in the form of used batteries.

A certain solution to the problem can be found in the growing market of BLE devices. For example, battery-powered beacons can be supported by solar energy harvesters [16]. The use of such a support extends the time between subsequent system services. However, it is impossible to effectively use photovoltaic cells in dark rooms, such as basements, bathrooms or corridors, where daylight has no access, and artificial light is on for a short time [17]. Another solution is to use the beacons in a network of special transmitters or Wi-Fi access points. The electromagnetic field generated by these devices can be converted into the energy used to power the beacons [18]. Such a solution requires an extensive network of transmitters, which must be connected to the main power supply. It is associated with large costs, and such an installation is difficult to implement in some rooms. Another problem is the need to cover a large space with a signal, which may lead to exceeding the radiation limits and cause interference between existing wireless networks [19,20].

It can be found in scientific papers that electronic tags may be powered by using the heat-flow phenomena [21]. For example, the thermo-generator in the form of a Peltier module is able to provide enough energy to power sensors that wirelessly transmit measurement results [22,23]. Therefore, the authors consider in this paper the possibility of supporting the beacon power supply with energy from a thermoelectric harvester. The temperature differences in the environment can be generated by heat losses from different types of devices, such as light bulbs, computers, motors, refrigerators, radiators, building installation pipes, etc. Devices that intentionally heat or cool rooms, such as heaters, radiators or air-conditioners, can also be considered as a potential energy source. The only condition is to ensure the heat flows through the thermoelectric generator.

In this paper, the current consumption of an exemplary beacon that sends a signal with different powers and in different time intervals was measured in order to determine its energy demand. The voltage and current produced by the Peltier module were also measured by applying the increasing temperature differences to the surfaces of the Peltier cells. The experiments were performed for several load resistances to determine the current efficiency of the module. In this way, it was estimated how much energy could be obtained from the heat flow occurring in the beacon's surroundings. In consequence, it was experimentally proven that the environmental conditions in the vicinity of the beacons are sufficient to power them. Even temperature differences of several degrees Celsius is enough to generate a sufficient amount of energy, especially when a boost converter is used in the supply to increase the voltage.

At the beginning of this paper, the experimental stage of the research is described (Section 2). The necessary preliminary tests are performed using example products of beacons and Peltier modules acquired from the commercial market. The energy demand of the load and the energy supply of the power source under given temperature differences and load conditions are detailed and analyzed. In addition, the setups of the laboratory stands are presented and justified in detail. The conclusions drawn from the results obtained in the measurements are explained in depth in Section 3. On this basis, it is proven (Section 4) that the beacon can be powered from the Peltier module using the environmental conditions of the navigation system inside the building just by placing the transmitter on an object whose temperature differs from the ambient temperature. In order to evaluate the elaborated conception, the model of the proposed system is developed. Thus, the simulations provided in Section 5 confirm that the proper operation of the beacon with the Peltier module is possible in real applications.

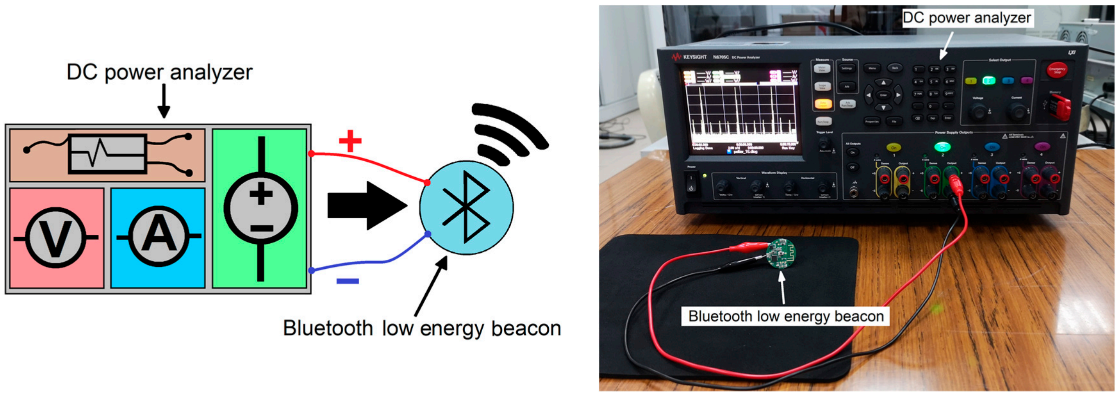
2. Materials and Methods

In order to determine the energy demand in an exemplary beacon, the Global Tag (Brescia, Italy) GT-DKBY_A-BLE product was tested (Table 1). This device is an electronic circuit assembled on a PCB with a diameter of 32 mm. The main component is the Nordic (Trondheim, Norway) NRF51810 microcontroller with an integrated Bluetooth interface. This interface works with the antenna to create a path on the PCB and communicates in the Bluetooth 4.2 low energy standard (IEEE 802.15.1) in the frequency band of 2400–2483.5 MHz. The beacon is powered by a CR2031 lithium battery with a voltage of 3 V. The total thickness is approximately 10 mm [24].

Table 1. Parameters of the tested products.

Product	Characteristics
GT-DKBY_A-BLE BLE beacon	Producer: Global Tag (Brescia, Italy) Standard: Bluetooth 4.2 low energy standard (IEEE 802.15.1) Frequency band: 2400–2483.5 MHz Control unit: Nordic (Trondheim, Norway) NRF51810 microcontroller Power supply: 3 V CR2031 lithium battery Dimensions: 32 mm diameter, 10 mm thickness
TEC-12706 Peltier module	Producer: TEC Microsystems, Berlin, Germany Maximum operating temperature: 125 °C, 150 °C or 200 °C Maximum temperature difference: 70 K Supply voltage: 0–15.5 V Maximal power: 60 W Maximal current: 6 A Dimensions: 40 mm by 40 mm and 3.9 mm thickness

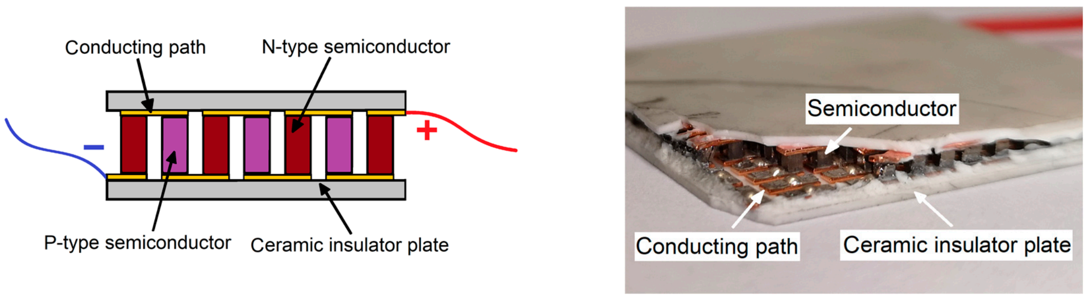
The current consumed by the GT-DKBY_A-BLE beacon was measured for four different settings of the transmitted signal power level and for four different time intervals between successive transmissions. Since the time interval can be set from 0.1 s to 10 s with a step of 0.1 s, it was decided to take measurements for time values equal to 0.2 s, 1 s, 2 s and 4 s. The signal strength was sequentially set to 4 dBm, 0 dBm, −6 dBm and −23 dBm. The current consumption was measured using the N6705C DC (by Keysight, Santa Rosa, CA, USA) power analyzer. The diagram of the measuring equipment is shown in Figure 1a, and Figure 1b shows a photo of this stage. The beacon was powered with a constant voltage of 3 V from a programmable power supply built into the power analyzer. The measurement range was from 0 mA to 100 mA, and samples were taken every 0.02 ms.



(**a**) (**b**)

Figure 1. Test equipment for measuring the current consumed by the beacon: (**a**) Diagram; (**b**) Laboratory stand.

The Peltier module in typical applications works as a heating or cooling device due to the Peltier effect. The current flow through the module causes heat transfer from one of its surfaces to another. This process requires the supply of electricity. The Peltier module diagram is shown in Figure 2a. It is constructed of two parallel, electrically non-conductive plates on the surface of which conductive paths are applied. These traces electrically connect p-type and n-type semiconductors in series. A photo of a device with one plate partially removed to reveal the internal components is shown in Figure 2b.



(**a**) (**b**)

Figure 2. Peltier module: (**a**) Diagram; (**b**) Photograph revealing the internal components.

Placing semiconductor junctions in areas of different temperatures results in the movement of charge carriers between these areas and the creation of an electromotive force. This voltage is proportional to the Seebeck coefficient S (1), which determines the ratio of the electromotive force difference $\Delta\phi$ to the temperature difference ΔT and depends on the type of materials forming the junctions:

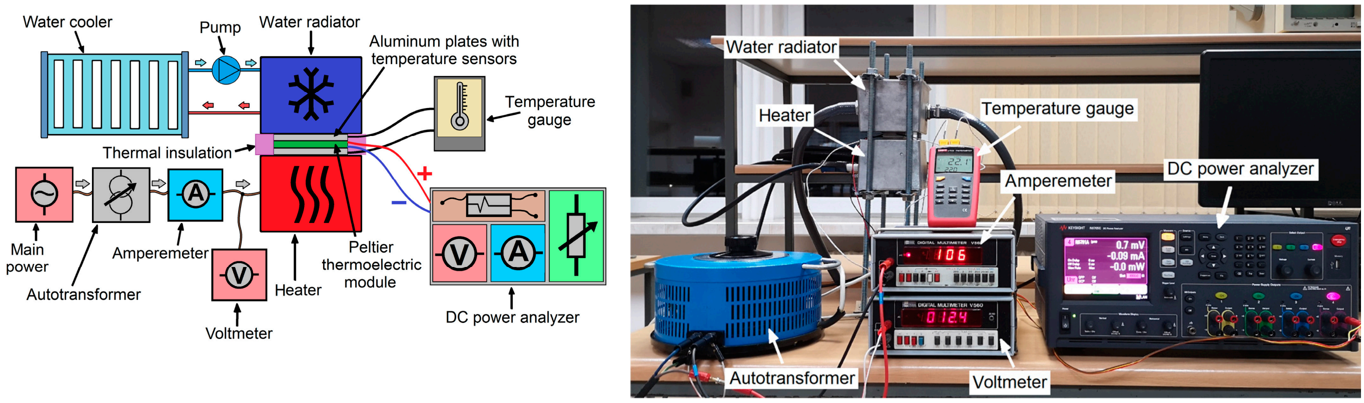
$$S = \frac{\Delta\phi}{\Delta T}. \tag{1}$$

The voltage on the Peltier module terminals is a multiple of the voltage obtained from one pair of junctions.

A TEC-12706 (by TEC Microsystems, Berlin, Germany) module with dimensions of 40 mm by 40 mm and 3.9 mm thickness was used in the measurements (Table 1) [25]. Since the semiconductors are soldered with tin containing an admixture of bismuth (BiSn), which melts at 138 °C, the maximum operating temperature of the device is below 138 °C. The insulator plates are composed of aluminum oxide (Al_2O_3). According to Figure 2b and the identification number of the module, 127 pairs of internal semiconductor junctions are connected in series. The Seebeck coefficient for one semiconductor junction is approximately several hundred microvolts per Kelvin, so the module as a result of heat flow should generate several dozen millivolts per Kelvin of the temperature difference between its surfaces [26,27].

In order to determine how much energy can be obtained from a Peltier module under a given temperature and load conditions, the measurements were performed using the N6705C power analyzer with a built-in programmable dummy load for load resistances of 50 Ω, 100 Ω, 250 Ω, 500 Ω, 1 kΩ, 2 kΩ, 4 kΩ and 8 kΩ. The voltage at the module terminals and the intensity of the electric current were measured, depending on the temperature difference between the surfaces of the cells. The temperature was monitored using a UNI-T UT325 (by Uni-Trend Technology, Dongguan, China) meter with thermocouples.

The measurement setup is shown in Figure 3. A heating element with adjustable electric power is attached on one side of the Peltier module. On this surface, an even temperature distribution is kept by applying an aluminum plate that uniformly transfers heat to the cells. A temperature sensor is placed tightly between the aluminum plate and the module. The power of the heater is regulated with an autotransformer; the voltage values and the intensity of the flowing current are monitored by laboratory apparatuses.



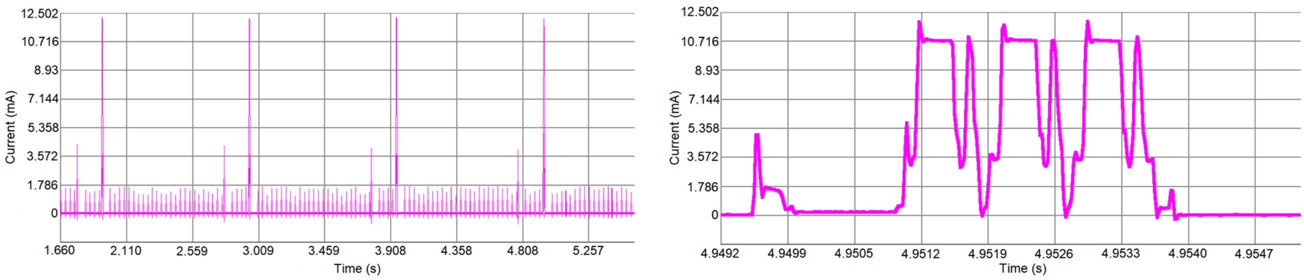
(**a**) (**b**)

Figure 3. System for measuring the energy generated by the Peltier module: (**a**) Diagram; (**b**) Laboratory stand.

The second surface of the Peltier module transfers heat to the water radiator also through an aluminum plate. The second temperature sensor is placed in the gap between the Peltier module and the aluminum plate. Water is pumped in a closed circuit between the radiator and the cooler. All contact surfaces of the elements are covered with thermally conductive paste to enhance the heat transfer. Between the heating and cooling elements around the module, an insulator is inserted to limit the heat flow in ways other than through the cells. This system keeps a constant temperature difference during the measurement process.

3. Results

The individual time waveforms of the current drawn by the beacon are similar to each other in terms of shape. They differ in only two characteristic elements when the time interval or signal strength is changed (0.2 s, 1 s, 2 s and 4 s or 4 dBm, 0 dBm, −6 dBm and −23 dBm, respectively). The differences are discussed on the basis of one example presented in Figure 4, generated at the time interval of the beacon signal equal to 1 s and the signal power equal to 0 dBm.



(**a**) (**b**)

Figure 4. Time-domain waveform of the current drawn by the beacon: (**a**) Four successive signal transmissions; (**b**) Zoom on a single pulse of signal transmission.

In Figure 4a, the waveform consists of a cyclically repeated series of pulses related to elementary operations in the signal transmission procedure. The frequency of the series of pulses is determined by the set time interval—this is the first characteristic element that differs between the individual registered current waveforms. The duration of the single transmission itself is independent of the settings and is equal to approximately 5 ms (Figure 4b). Thus, most of the time, the beacon is in sleep mode, and then the current consumption is reduced and averages 4.5 µA for all transmitter settings. This is the minimum current that is drawn by the transmitter (I_{bmin}).

The time waveform of the current drawn during a single signal transmission, which consists of a series of pulses, is shown in Figure 4b. The amplitude of the current pulses, which is dependent on the set power, is the second characteristic element that differs between the recorded waveforms. The maximum value of the current intensity I_{bmax}, the average value of the current intensity I_{bav} and the average power P_{bav} consumed by the beacon are listed in Tables 2–4. The above parameters are determined for different transmitter settings. As can be observed, the current consumption is not constant, and it depends on the performed operation. The beacon consumes the most power during the information broadcast, which is proportional to the set signal strength. The average power drawn is proportional to the set level of the signal strength and inversely proportional to the time interval (Table 4).

Table 2. Summary of the maximum current consumed by the beacon.

		Signal Power			
		−23 dBm	**−6 dBm**	**0 dBm**	**4 dBm**
Time interval	0.2 s	11.777 mA	11.594 mA	12.846 mA	18.319 mA
	1 s	11.774 mA	11.689 mA	12.429 mA	18.115 mA
	2 s	11.775 mA	11.871 mA	12.817 mA	18.437 mA
	4 s	11.654 mA	11.713 mA	12.765 mA	18.353 mA

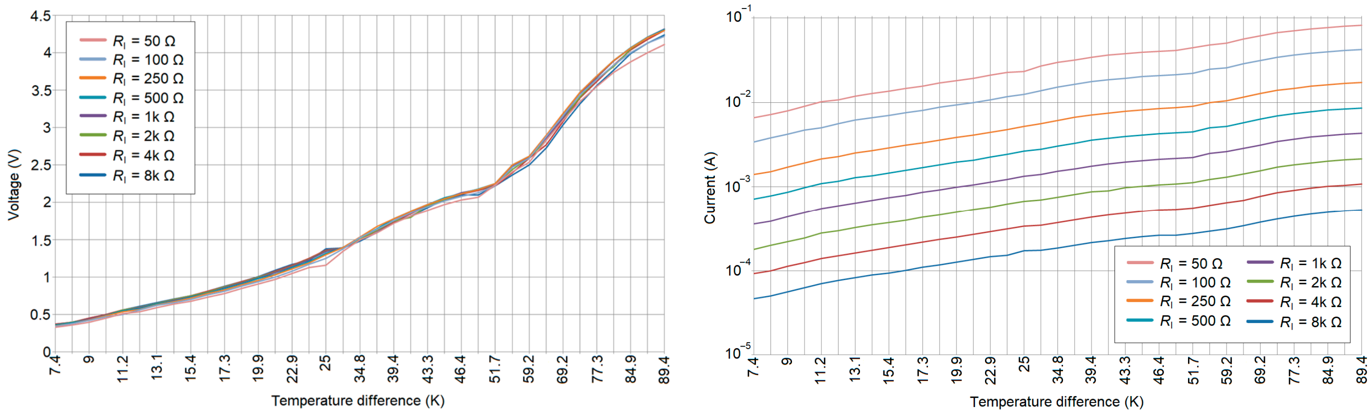
Table 3. Summary of the average current consumed by the beacon.

		Signal Power			
		−23 dBm	**−6 dBm**	**0 dBm**	**4 dBm**
Time interval	0.2 s	74.8 µA	82.8 µA	112.6 µA	154.5 µA
	1 s	18.8 µA	20.7 µA	28.2 µA	29.8 µA
	2 s	11.7 µA	12.6 µA	15.6 µA	19.6 µA
	4 s	8.2 µA	8.7 µA	10.5 µA	11.4 µA

Table 4. Summary of the average power consumed by the beacon.

		Signal Power			
		−23 dBm	**−6 dBm**	**0 dBm**	**4 dBm**
Time interval	0.2 s	224.4 µW	248.4 µW	337.8 µW	463.5 µW
	1 s	56.4 µW	62.1 µW	84.6 µW	89.4 µW
	2 s	35.1 µW	37.8 µW	46.8 µW	58.8 µW
	4 s	24.6 µW	26.1 µW	31.5 µW	34.2 µW

The voltage at the Peltier module terminals, depending on the temperature difference between its surfaces, is shown in Figure 5a, and the waveform of the current drawn from the cell versus the temperature difference between its surfaces is shown in Figure 5b. The measurements were taken for the constant load resistance R_l of 50 Ω, 100 Ω, 250 Ω, 500 Ω, 1 kΩ, 2 kΩ, 4 kΩ and 8 kΩ.



(**a**) (**b**)

Figure 5. Output characteristics of the Peltier module depending on the temperature difference between the surfaces of the module and different values of resistive load: (**a**) Voltage; (**b**) Current.

For each measurement point, the ratio of the electromotive force generated at the terminals of the tested module to the temperature difference is calculated. Then, the results are averaged, thus obtaining the thermoelectric coefficient S_p of the module, which for the tested TEC-12706 is equal to 46.4 mV/K. With a temperature difference of approximately 70 K, the output voltage of the cell reaches the nominal value needed to directly power the beacon, which is equal to 3 V. The obtained waveforms show that the change in load resistance has no significant effect on the output voltage, which proves the low internal resistance of the cells, amounting to approximately 2.4 Ω.

4. Discussion

Table 5 contains the estimated working time of the tested beacon when it is powered by a typical CR2032 lithium battery with different time intervals and transmitted signal power levels. The longest operating time is obtained with long breaks between the transmissions. Setting a high signal strength reduces the operating time.

Table 5. Summary of the operation time of a beacon powered by a CR2031 lithium battery with different time intervals and power levels of the transmitted signal.

		Signal Power			
		−23 dBm	**−6 dBm**	**0 dBm**	**4 dBm**
Time interval	0.2 s	122.5 days	110.7 days	81.4 days	59.3 days
	1 s	487.6 days	442.8 days	325.1 days	307.6 days
	2 s	783.5 days	727.5 days	587.6 days	467.7 days
	4 s	1117.9 days	1053.6 days	873.0 days	804.1 days

The experiment shows that it is possible to power the beacon from the Peltier module using the environmental conditions of the navigation system inside the building. By placing the transmitter on an object whose temperature differs from the ambient temperature, the heat flow from this object through the thermo-generator to the environment can be used to generate the energy needed for the transmitter to operate. This solution extends the working time between successive battery replacements and even eliminates the battery, which would make the system maintenance-free.

A schematic diagram of the Bluetooth low energy transmitter powered by the Peltier module is shown in Figure 6. The housing is divided into two parts, which are separated by thermal insulation. One part of the housing is used to attach the device to the object from which the beacon receives or gives off heat. The second part of the housing is used to exchange heat with the surrounding air. Inside the device, there is the Peltier module with surfaces attached to the previously mentioned elements of the housing. The heat flow through the device generates electricity, which is appropriately converted in the conditioning system. The conditioning system adjusts the voltage generated by the Peltier module to the nominal voltage of the transmitter. If the current demand for energy is greater than the energy obtained from heat, the conditioning module takes some of the energy from the storage, which can be in the form of a battery or a super capacitor. If the amount of power produced by the Peltier module exceeds the demand of the transmitter, then the conditioning system charges the storage element. When choosing a power source, the maximal high energy demand during a transmission has to be taken into consideration. High current pulses that exceed the capacity of the conditioning system may lead to device resetting.

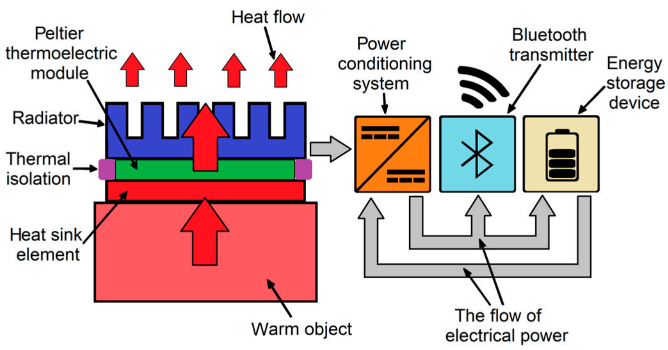


Figure 6. Schematic diagram of a beacon powered by a thermoelectric module.

The transmitter can be placed on objects that generate heat as a side effect of work or in which there is heat loss, for example light bulbs, refrigerators, motors and installation pipes. The transmitter may also be placed on devices whose purpose is to generate heat, such as radiators and heaters. In all cases, the thermal energy flowing through the beacon and powering it will be dissipated in the environment.

The beacon is powered by a constant voltage U_b. The current drawn by the beacon i_b depends on the time t. The energy E_b needed for one cycle of the transmitter's work is given by the Formula (2). A single work cycle is defined by two successive signal transmissions. The start time of the transmission of the first signal is marked as t_1, while t_2 denotes the start time of the next signal transmission.

$$E_b = U_b \int_{t_1}^{t_2} i_b(t)dt. \tag{2}$$

The energy E_p generated by the Peltier module in one beacon's work cycle depends on the load R_l connected to the module and the voltage u_p generated by the module:

$$E_p = \frac{u_p^2(\Delta T)}{R_l}(t_2 - t_1). \tag{3}$$

This voltage depends linearly on the temperature difference ΔT and the thermoelectric coefficient S_p, expressing the ratio of the electromotive force on the thermo-generator's leads to the temperature difference:

$$u_p(\Delta T) = S_p \cdot \Delta T. \tag{4}$$

Finally, the Formula (5) expresses the amount of energy obtained in one beacon's work cycle from a given Peltier module, depending on the load and temperature difference:

$$E_p = \frac{\left(S_p \cdot \Delta T\right)^2}{R_l}(t_2 - t_1). \tag{5}$$

The load resistance is the input resistance of the conditioning circuit. Assuming that the efficiency of the conditioning system is equal to 100% and to ensure the correct operation of the beacon, the energy E_p obtained from the cell during one cycle must be at least equal to the energy E_b consumed by the beacon during one cycle.

The maximum current i_{pmax} and the minimum current i_{pmin}, which are taken from the cell in given temperature conditions to power the beacon, are determined with the following Formulas (6) and (7):

$$i_{pmax} = \frac{U_b \cdot I_{bmax}}{S_p \cdot \Delta T}, \tag{6}$$

$$i_{pmin} = \frac{U_b \cdot I_{bmin}}{S_p \cdot \Delta T}, \tag{7}$$

where I_{bmax} is the maximum current consumed by the beacon during signal transmission, which depends on the set transmitter power, and I_{bmin} is the minimum current consumed by the beacon during reduced power consumption between transmissions, which is the same for each transmitter power setting. Relations (6) and (7) are presented in Figure 7 as characteristics in the temperature domain. When plotting the characteristics, the maximum value of the current drawn by the beacon was substituted into the Formula (6) with the average value of the current calculated from the maximum values of the current drawn at different time intervals for one power level (Table 6).

The area between the waveform plotted using the Formula (7) and the waveforms plotted using the Formula (6) for different I_{bmax} values is the working area of the beacon. Since the current operating area and ambient temperature conditions of the system are determined, the power conditioning device can be appropriately selected.

Due to the low internal resistance of the Peltier module with the use of an appropriate conditioning system, temperature differences of several Kelvin are sufficient to power the beacon. With temperature differences less than 70 K, the voltage obtained from the cell is low compared to the nominal voltage of the beacon. The higher the temperature difference, the closer the voltage on the Peltier module is to the nominal voltage of the transmitter. This means that voltage does not have to be intensively increased by the conditioning system, which in turn results in a lower current load on the thermo-generator. With a temperature difference of 70 K, the Peltier module generates enough voltage to power the beacon directly.

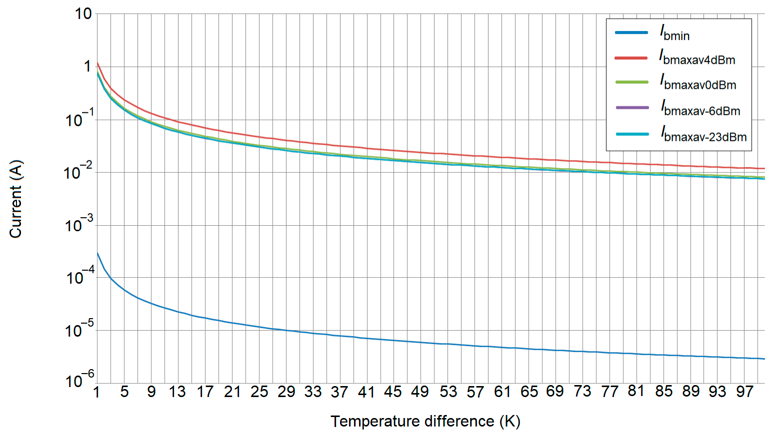


Figure 7. Characteristics showing the maximum and minimum current drawn from the thermogenerator, depending on the temperature difference between its surfaces.

Table 6. The average maximum current consumed by the beacon, calculated from the maximum currents for different time intervals and the same transmitted signal power level.

Signal Power	**−23 dBm**	**−6 dBm**	**0 dBm**	**4 dBm**
Average of the maximum current	$I_{bmaxav-23\text{dBm}}$	$I_{bmaxav-6\text{dBm}}$	$I_{bmaxav0\text{dBm}}$	$I_{bmaxav4\text{dBm}}$
	11.745 mA	11.717 mA	12.714 mA	18.306 mA

5. Evaluation

In order to evaluate the elaborated conception, the model of the proposed beacon with the Peltier module used as a power supply instead of a traditional battery is developed. Since the Peltier module is a weak source of voltage, a step-up DC-to-DC converter (boost converter) is used as a conditioning system.

The most important factor of the system's operation is the energy balance; the power generated by the Peltier module P_p has to be equal to the power consumed by the beacon P_b:

$$P_p = P_b => i_p \cdot S_p \cdot \Delta T \cdot \frac{R_L}{R_L + R_i} = U_b \cdot i_b \tag{8}$$

where i_p is the current drawn from the Peltier module, S_p is the thermoelectric constant of the Peltier module determined from the measurements, ΔT is the temperature difference across the Peltier module, R_L is the load resistance, R_i is the internal resistance of the Peltier module, U_b is the nominal supply voltage of the beacon and i_b is the current drawn by the beacon.

The conditioning system maintains the beacon supply voltage at the nominal level despite changes in the temperature difference (and thus the output voltage) on the Peltier module. The lower voltage is compensated by the higher current i_p. Based on the measurements of the i_b and U_p parameters (Section 3), it is shown that the beacon can be powered by the Peltier module, but the conditioning system should be used. For the worst case, the highest current I_{bmax} drawn by the beacon is equal to 18.306 mA at a power transmission set to 4 dBm, whereas the minimum value I_{bmin} drops to 4.5 µA in the idle mode. Then, the average current I_{bav} equals 29.8 µA at a 1 s interval ($t_2 - t_1$):

$$I_{bav} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} i_b(t) \tag{9}$$

With regard to the Peltier module, the i_{pmax}, i_{pmin} and i_{pav} curves at a given ΔT are calculated from the energy balance relationship (8). The diagram shown in Figure 8 is obtained at R_L = 50 Ω and R_i = 2.4 Ω, which describes the worst case of system operation.

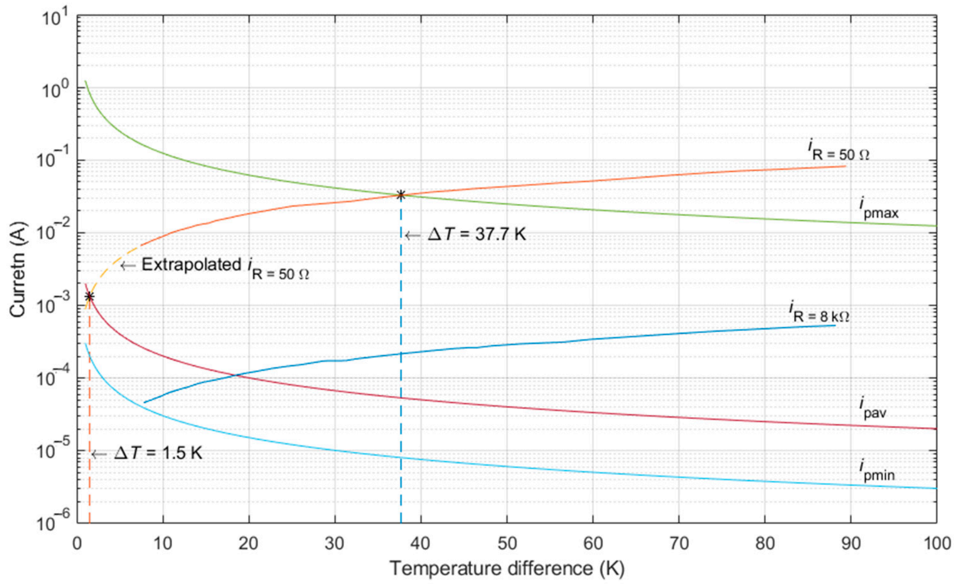


Figure 8. Operating point of the system.

The operating point of the system is set in the area between the i_{pmin} and i_{pmax} curves. It determines the load of the Peltier module (and consequently the power range) that is possible at a given temperature difference. The measured waveform of the i_R current at the 50 Ω load resistance is also shown in Figure 8. In the experiment, the smallest temperature difference was equal to 7.4 K. Therefore, this course is extrapolated for lower temperature values using the following formula:

$$i_{extR=50\Omega} = \frac{S_p \cdot \Delta T}{R_L + R_i}, \tag{10}$$

In the case of small temperature differences and, as a consequence, too low voltage at the terminals of the Peltier module, the boost converter increases the supply voltage at the expense of higher current consumption. The operating area is bounded by the i_{pmax} and i_{pmin} curves as well as the straight line parallel to the vertical axis passing through the intersection point of the i_{pmax} and i_R curves. The temperature difference in this case has to be greater than 37.7 K. At lower temperature differences, the current efficiency of the Peltier module is too small to keep the energy balance. The use of an energy storage capacitor at the converter output may improve the system's efficiency. The energy gathered in the capacitor covers the temporary increased demand during signal transmission, and the system may operate on the i_{pav} curve. In this case, the system can work at a temperature difference equal to 1.5 K.

The assumed input voltage for the boost converter corresponds to the range that can be generated by the Peltier module. The values of this parameter start from U_{pmin} = 69.6 mV up to a maximum of U_{pmax} = 3 V, which corresponds to the temperature differences on the module terminals from 1.5 K to 64.7 K. The nominal output voltage from the boost converter is equal to U_b = 3 V, and this is the nominal supply voltage of the beacon. The maximum load generated by the beacon is determined as the average value of current consumption when sending the signal with a power of 4 dBm and a time interval equal to 1 s. The maximum value of this current is equal to I_{bmax} = 18.3 mA. The pulse duty cycle D of the transistor key in the boost converter is calculated for the minimum voltage generated by the Peltier module (the worst case of boost converter operation), and the assumed converter efficiency η = 90% is as follows [28]:

$$D = 1 - \frac{U_{pmin} \cdot \eta}{U_b} = 1 - \frac{69.6\ \mathrm{mV} \cdot 0.9}{3\ \mathrm{V}} = 0.98 \quad (11)$$

The ripple of the inductor current is taken as 20% of the maximum current drawn by the beacon:

$$I_{Lripple} = 0.2 \cdot I_{bmax} = 0.2 \cdot 18.306\ \mathrm{mA} = 36.6\ \mathrm{mA} \quad (12)$$

Then, the minimum value of the inductor inductance is calculated on the basis of the following formula:

$$L = \frac{U_{pmax} \cdot (U_b - U_{pmin})}{I_{Lripple} \cdot f_s \cdot U_b} = \frac{3\ \mathrm{V} \cdot (3\ \mathrm{V} - 69.6\ \mathrm{mV})}{36.6\ \mathrm{mA} \cdot 50\ \mathrm{kHz} \cdot 3\ \mathrm{V}} = 1.6\ \mathrm{mH} \quad (13)$$

The f_s keying frequency is assumed to be equal to 50 kHz. The ripple value of the beacon supply voltage is determined as 5% of the nominal supply voltage of the beacon:

$$U_{bripple} = 0.05 \cdot U_{bm} = 0.05 \cdot 3 = 0.15\ \mathrm{V} \quad (14)$$

The minimum capacitance of the output capacitor is calculated from the formula:

$$C = \frac{I_{bmax} \cdot D}{f_s \cdot U_{bripple}} = \frac{18.306\ \mathrm{mA} \cdot 0.98}{50\ \mathrm{kHz} \cdot 0.15\ \mathrm{V}} = 2.39\ \mu\mathrm{F} \quad (15)$$

For such parameters of the system, calculations are performed in the Matlab/Simulink environment. In the diagram (Figure 9), the Peltier module is shown as a voltage source, and the beacon is presented as a resistive load.

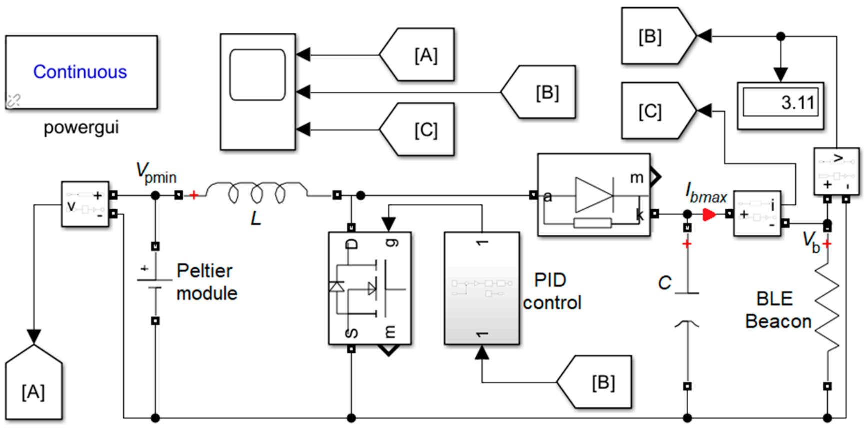


Figure 9. Model of the beacon powered by the Peltier module simulated in Matlab/Simulink.

It should be emphasized that the model parameters of the boost converter components are selected on the basis experiments in which (1) the voltage generated by the Peltier module and (2) the current consumed by the beacon were measured. The simulations confirm that all components are selected correctly; the voltage and power at the converter output are constantly kept at a level that ensures the proper operation of the beacon despite the changes in the voltage generated by the Peltier module in the range of 69.6 mV to 3 V.

6. Conclusions

Maintenance related to the operation of beacons, which are key elements of indoor navigation systems, is associated with high costs. The use of heat losses reduces the costs of purchasing and replacing batteries in the transmitters. The Peltier module, to which the appropriate temperature difference is applied, is able to produce enough energy to power the beacon. However, it should be remembered that the electrical energy generated by the Peltier module is the result of heat flow. Some of the heat is converted into electricity. Lower load resistance causes a greater flow of charges in the semiconductor junctions. The chargers, among others, transfer thermal energy that, in turn, causes faster temperature equalization on both sides of the Peltier cells. The problem with maintaining the temperature difference arises in the case of small load resistances and small temperature differences.

The most important advantages of the concept are the elimination of the need for periodic battery replacement, the reduction in the maintenance costs of indoor navigation systems as well as environmental protection against waste batteries. It should be noted that there are a multitude of heat-generating devices in the environment to which the beacon with the Peltier module can be attached. For example, the beacons can be used to build the node network in a smart home for providing information for artificial intelligence [11,12]. Heating radiators, all kinds of light bulbs including energy-saving LEDs, all household appliances with control systems, computers, etc., are natural localizations for the nodes. The developed beacons may also act as sensors in surveillance installations, e.g., for the management of photovoltaic power plants. Every PV panel is a source of quite a large amount of heat that has to be dissipated to the environment. Equally effective operation of the device could be achieved by placing it on the hot engines of mobile vehicles. The ability to identify moving vehicles is one of the concerns of the modern automotive industry. Thus, the most important challenge in the development of the proposed beacon concept is its implementation in a real application.

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