Chapter

Supercapacitors as Guarantors for Energy Sustainability in Low-Power Energy Harvesting Sensor Modules

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Abstract

Energy harvesting, low-power sensor modules are characterised by their energy independence, power consumption, size, robustness to withstand the environmental conditions, maintenance demand and long term operation. To secure any of these conditions focus has to be put on the device energy reservoir. Traditional approach would reach for the battery and at the very beginning of the development, accept the limitations that go along with it. These limitations in form of high temperature difference dependency, current peaks, limited charge cycles, loss of operating voltage and capacity, soon become constraints in the sensor module life cycle. Answer to these constraints and a guarantor of a long sensor module life cycle is a supercapacitor. An energy storage which does not have any special charging requests, other than ensuring that the maximum voltage is not exceeded, or that a minimum voltage is not reached. Supercapacitors have a low ESR (equivalent series resistance), typically of the order of 100 mΩ. This reduces internal losses during charge and discharge cycles allowing them to handle current surges without the output voltage dropping significantly. Lithium-ion supercapacitors especially have good self-discharge characteristics and retain their voltage for years.

Keywords: energy harvesting, lithium-ion supercapacitor, self-discharge characteristics, leakage current, low power, EnOcean sensor module

1. Introduction

LPWAN (low-power wide-area network) is a current research topic, alongside with the growth and popularity of the Internet of things (IoT). The main focus is the core element behind each of these aspects, i.e. the sensor node. A sensor node, which can be observed as either an independent unit, or part of a LPWAN, performs many tasks. It can harvest energy, give power to attached sensors, collect and process data from these sensors and transmit it through the air, while sustaining its own power management [1, 2]. Application fields of the IoT world are constantly expanding and with it, researched sensor platforms [3–5].

The majority of these sensor platforms rely on batteries as the main power supply. This is considered the traditional approach in sensor module energy management development [6, 7]. Problems with batteries are well known [8, 9] and thus research is now directed towards finding energy storage alternatives for use in low power sensor modules. An effective alternative is supercapacitors.

The advantages of supercapacitors are also recognised by the authors of [10]. Some of these include, very high rates of charge and discharge, little degradation of capacity over hundreds of thousands of cycles, low toxicity of materials used, high cycle efficiency (95% or more). Authors of [9] highlight the use of a supercapacitor instead of a battery to secure long term operation. This is described as the main advantage of their wireless sensor node. One of the disadvantages of supercapacitors, besides the currently higher price, is that their energy density today remains less than that of batteries, by an order of magnitude [9]. Since a supercapacitor is usually used in conjunction with a suitable solar cell, this lower energy density drawback is overcome. The potential of a lithium-ion supercapacitor is investigated in this chapter as the main energy storage for low-power, energy harvesting, wireless sensor modules.

2. Energy storage characterisation

Compared to supercapacitors, batteries have many limitations when used in outdoor sensor modules. During each transmission, current peaks in low power sensor modules can easily reach 40 mA [1, 11]. This is a serious disadvantage when utilising batteries, as they are very sensitive to current peaks. Current peaks above 30 mA limit their life cycle [8, 12], and batteries already have a lower life cycle, and are highly dependent on the number of recharge/discharge cycles. For example, the lithium-ion battery, whose characteristics are shown in **Figure 1**, can be recharged from 4000 to 7000 times. This depends on whether the previous discharge levels were less or greater than 50% respectively. After a certain period of time batteries lose their capacity and their nominal operating voltage becomes degraded, and thus will require replacement [8]. On the other hand, a

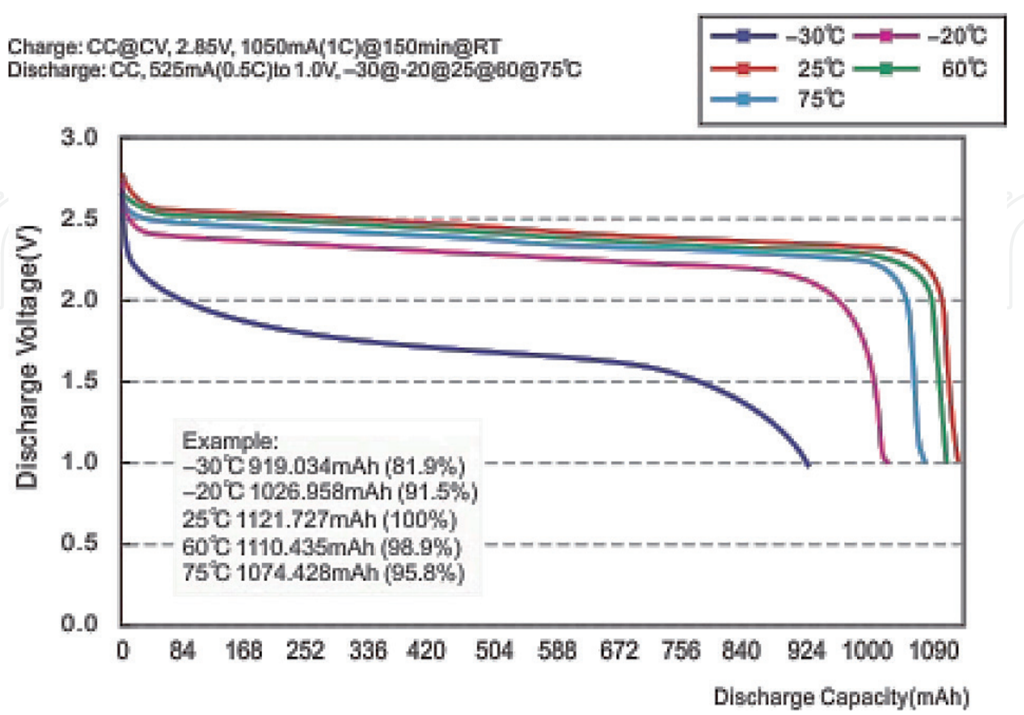

Figure 1.
Discharge temperature characteristics of the lithium-ion rechargeable battery Huahui HTC0407 with a life cycle between 4000 and 7000 times [14].

Type	Technology	Voltage (V)	Capacity (mAh)	Measured impedance (Ω)	Self-discharge	Comments
ML2430	Manganese lithium	3.1	100	≈13	2%/year	Measured 0.2 V voltage drop at 40 mA
VL2320	Manganese lithium	3.1	30	≈30	<2%/year	Too high impedance
MS920SE	Manganese lithium	3.1	11	≈35	2%/year	Too high impedance
LIR1220	Lithium-ion	3.6	8	<2	7%/month	Self-discharge values from <2%/year to 7%/month
CP1624	Lithium-ion	3.6	50	<1	20%/year	20% self-discharge per year is equivalent to steady 1 μA

Table 1.
Comparison of different technologies used for energy storage.

supercapacitor can be charged and discharged virtually an unlimited number of times. Due to this, information concerning supercapacitor life cycle is not usually provided in their specification. For example, for the used supercapacitor, the only information available regarding its life cycle, is that after 10,000 charge/discharge cycles the supercapacitor will still maintain a minimum 70% of the initially specified capacitance [13]. **Figure 1** displays a typical battery discharge curve. After full charge and start of operation there is an initial voltage drop, after which the battery voltage is stable. At a point towards the end of the lifecycle, another voltage drop will occur. The battery supply voltage will fall below the nominal voltage, and the battery will require replacement. Within the same figure, one can also see another disadvantage of batteries, the huge battery capacity temperature dependency (especially at negative temperatures).

Supercapacitors, on the other hand, do not have any special charging requests, except ensuring that the maximum voltage is not exceeded, or that the minimum operating voltage is not reached. Supercapacitors have a low ESR (equivalent series resistance); typically below 100 mΩ. This reduces internal losses during charge and discharge cycles, thus allowing them to handle current surges without the output voltage dropping significantly [8].

Different types of energy storage have been investigated. A comparison is displayed in **Table 1**. Besides internal impedance, leakage current is the most important criteria when selecting an energy store for a low power sensor module.

Based on **Table 1** and **Figure 2** it is evident that the energy storage with lithium-ion technology is the most promising for use in low power sensor modules. **Figure 2** depicts why some types of energy storage should be avoided in energy harvesting devices. The generated electrical current from a small solar cell (photo current) is shown in the same figure, assuming a worst case scenario with indoor conditions (solar cell illuminated 4 hours with only 500 lx per day). It can be seen that this harvested photo current would be completely consumed by the leakage current of, e.g., NiCad (Nickel-cadmium)-based energy storage device.

Generally, only a low impedance energy storage with minimum leakage current and sufficient capacity, is able to deliver the required energy to power-up sensors and transmit data over a longer period of time [15]. Due to limitations

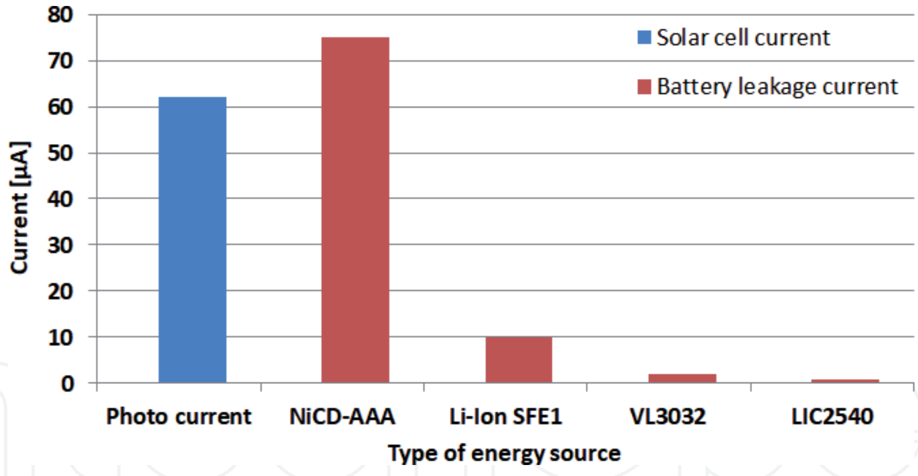

Figure 2.
Measured leakage currents of different energy stores, compared to the generated photo current from a small solar cell.

mentioned above, the tested batteries are deemed unacceptable energy storage solutions. Therefore, an alternative, with capacitor-like characteristics, is investigated.

3. Lithium-ion supercapacitors

A lithium-ion supercapacitor LIC1235RS3R8406 from Taiyo Yuden is selected as the main energy storage and became the 'heart' of the developed EnOcean low power, energy harvesting sensor module. Lithium-ion capacitors are hybrid capacitors, featuring the best characteristics of both EDLC (electrical double layer capacitors) and lithium-ion secondary batteries (LIB). Some of these characteristics are outlined in **Table 2** [13].

3.1 Self-discharge properties

Figure 3 shows the self-discharge property of the two different capacitor types. The cylinder type lithium-ion capacitor (LIC) has a 40 F capacity, when charged for 24 hours with 3.8 V, at a temperature of 25°C. The other, is a symmetrical type EDLC whose capacitance is similar to that of the lithium-ion capacitor. As seen here, the symmetrical type EDLC has a large self-discharge. After a month at 25°C, its operating voltage decreased to 80% of the initial voltage. In contrast, the LIC displays a far better self-discharge behaviour. At 25°C, it can maintain a voltage higher than 3.7 V, even after 100 days since full recharge [16]. Two additional self-discharge properties of the LIC, at two different temperatures, are also given in **Figure 4** (nominal capacity is 200 F). It is clear that after 4000 hours (at 60°C), the supercapacitor maintains close to 90% of its initial voltage. At 25°C it behaves even better; preserving 96% of the initial voltage.

The voltage retention behaviour of the lithium-ion capacitors is shown in **Figure 5**. After 22,000 hours at 25°C, this 100 F supercapacitor maintained 92% of the initial voltage [16].

The selected supercapacitor has a capacity of 40 F and this value is in the first order price compromise, compared to the 100 and 200 F versions. On the other hand a larger capacitance is not needed, since the consumption of the developed EnOcean sensor module is optimised and long term operation is secured. With the development of a more energy consuming sensor module [17], a supercapacitor with a higher capacity could be considered. The supercapacitor remains the most expensive component on the sensor module PCB, contributing to 20% of the overall costs of the assembled PCB.

3.2 Supercapacitor's leakage current

It is assumed that the sensor module due to its energy harvesting capabilities will be primarily used outdoors. Therefore, it is of great interest to define the supercapacitor's leakage current over a larger temperature range. Recorded measurements show that during a bright and sunny day, the temperature inside the sensor module housing can reach almost +70°C with direct sunlight (**Figure 6**).

	Items		Specifications
1	Operating Temperature Range (°C)		-30 ~ +85
2	Upper limit Voltage (V)		3.8
3	Lower limit Voltage(V)		2.2
4	Initial Characteristics	Capacitance	36-44F
		DCR	Under 125mΩ
5	Soldering Heat Resistance	Capacitance	Within initial spec
		DCR	Within initial spec

Table 2.
Main characteristics of the LIC1235RS3R8406 [13].

Figure 3.
Self-discharge property of the cylinder type lithium-ion capacitor with 40 F (150 mΩ) versus the EDLC with a similar capacitance [16].

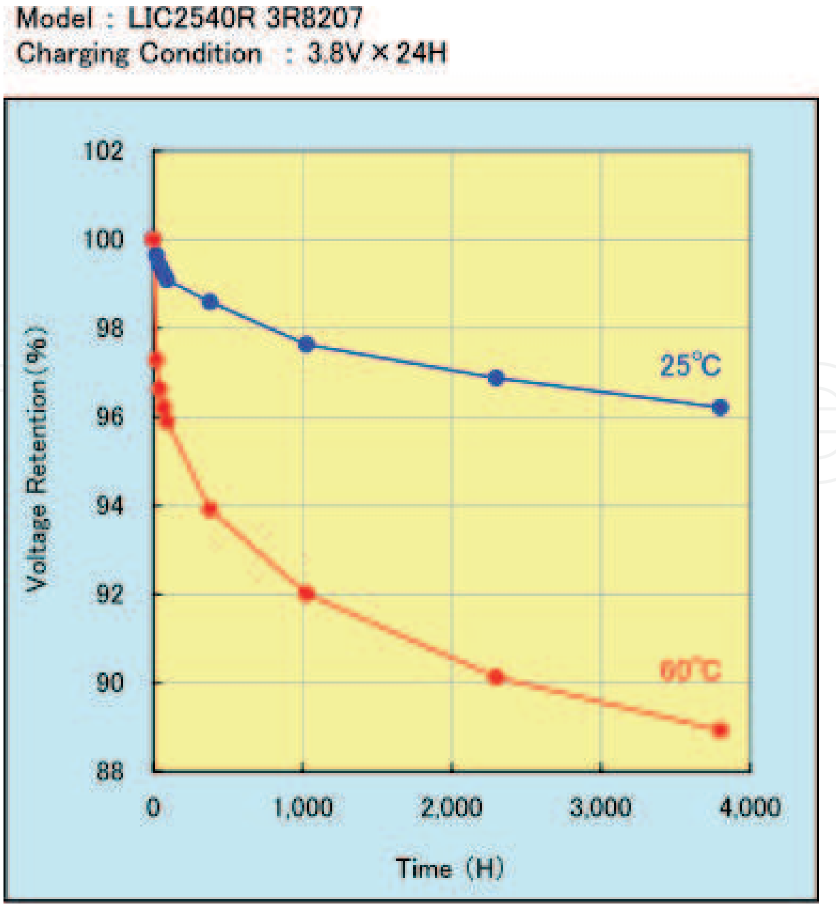

Figure 4.
Self-discharge characteristic of the 200 F (50 mΩ) Taiyo Yuden lithium-ion capacitor for two different temperatures [16].

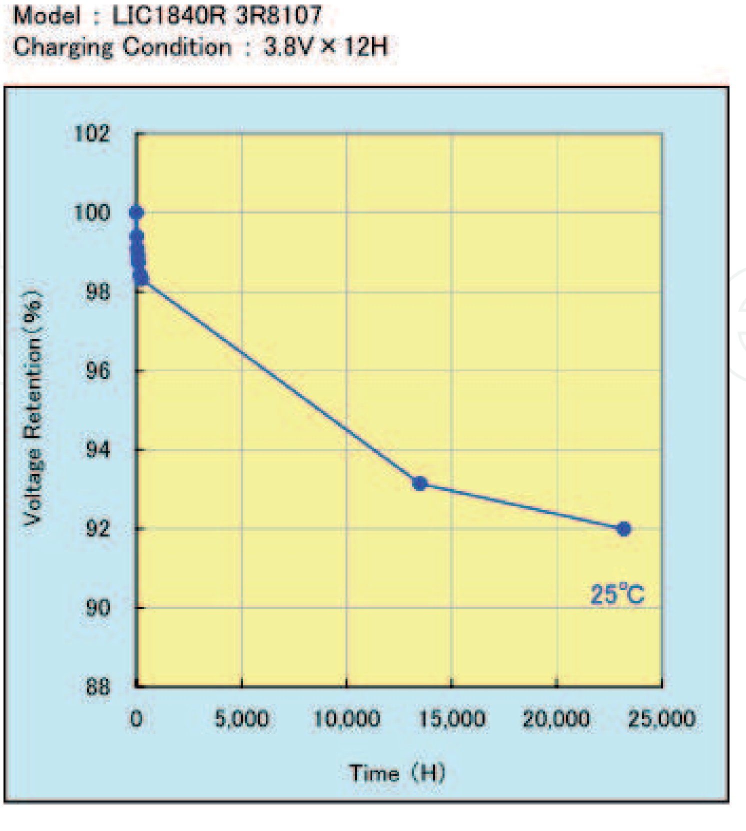

Figure 5.
Self-discharge characteristic of the 100 F (100 mΩ) Taiyo Yuden lithium-ion capacitor at 25 °C [16].

Figure 6.
Measuring temperature inside the EnOcean low power, energy harvesting sensor module housing. The two channels of the thermometer (yellow device) are measuring the temperature of the solar cell (52.3°C) and supercapacitor (50.1°C), respectively. The outside temperature was 30°C.

Temperature [°C]		85	70	60	45	25	0	-25
Leakage current after 8h [µA]	3.8 V	31.0	7.8	4.3	3.5	2.1	0.4	< 0.1
	3.5 V	12.6	3.7	1.9	0.7	0.4	< 0.1	< 0.1

Table 3.
Supercapacitor leakage current measured over different temperatures, for two different supercapacitor voltages [1].

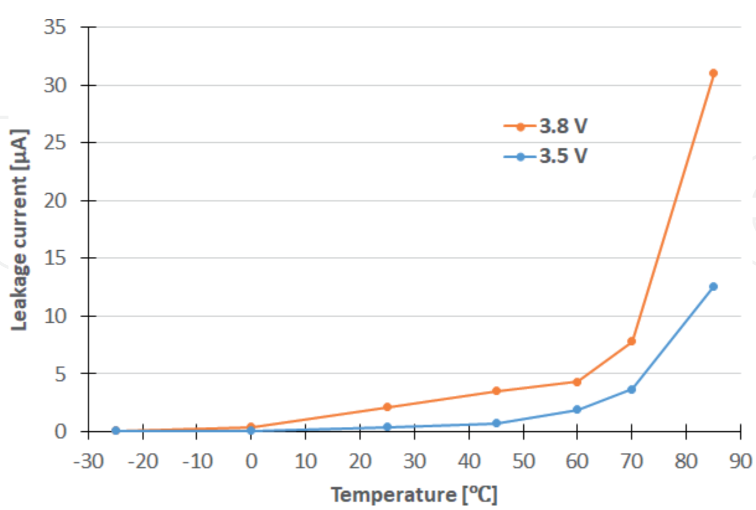

Figure 7.
Supercapacitor leakage current values over different temperatures for different voltage levels. This is a graphical representation of the results from ***Table 3****.*

A high temperature can have several negative effects on supercapacitor behaviour: the internal direct current resistance (DCR) increases, the equivalent series resistance (ESR) increases and the capacitance decreases [16]. Taking the aforementioned into consideration, the supercapacitor's leakage current over different temperatures has been measured and displayed in **Table 3** and **Figure 7**.

Measurements are taken for two different voltages of the supercapacitor; 3.8 V as the maximum usable voltage, and 3.5 V as the voltage just below maximum operating voltage. The voltage of the supercapacitor was kept constant, while the temperature was altered every 8 hours. During the last 1000 seconds of each cycle, the leakage current (current drained by the supercapacitor from the power source) was measured every 10 seconds and an average was calculated. As it can be seen in **Table 3** and **Figure 7**, a drastic increase in the supercapacitor's leakage current is observed at +85°C, compared to 25°C or lower. The supercapacitor's leakage current contributes to 40% (at 25°C) of the sensor module's overall current consumption during deep sleep mode. Therefore this must be considered when estimating dark run time operation (energy harvesting disabled).

4. The 100 Hour leakage current test

To measure the real use case behaviour of the supercapacitor and obtain its realistic leakage current figure, an additional 100 hours test was conducted. Charge and discharge cycles remaining within the supercapacitor's defined operating voltage range (from 2.2 to 3.8 V) have been executed. This was done using an automated test created with LabVIEW, as shown in **Figure 8**. For 5 hours at room temperature, a 3.8 V supply voltage was applied to the

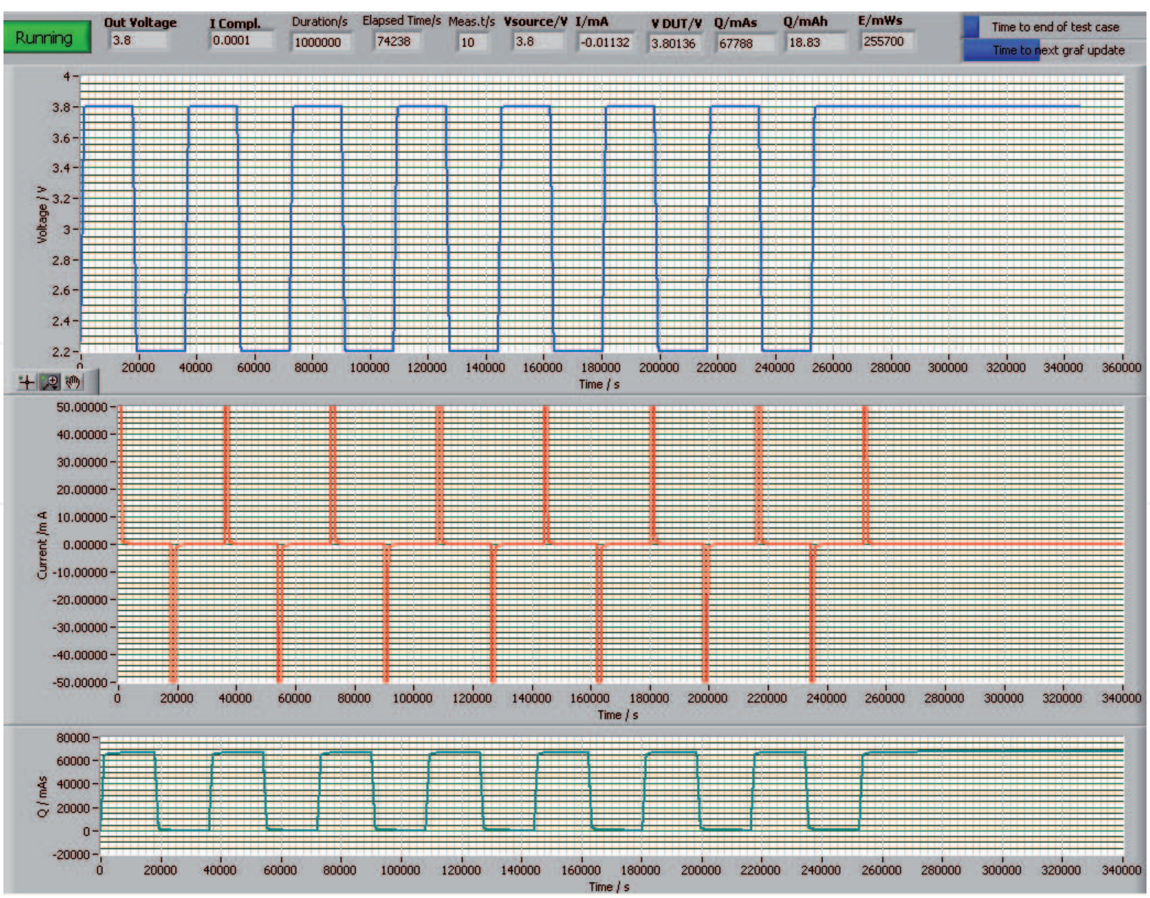

Figure 8.
Cycles of charge and discharge of supercapacitor. The blue, red and green lines represent the applied voltage, current drawn and available charge, respectively.

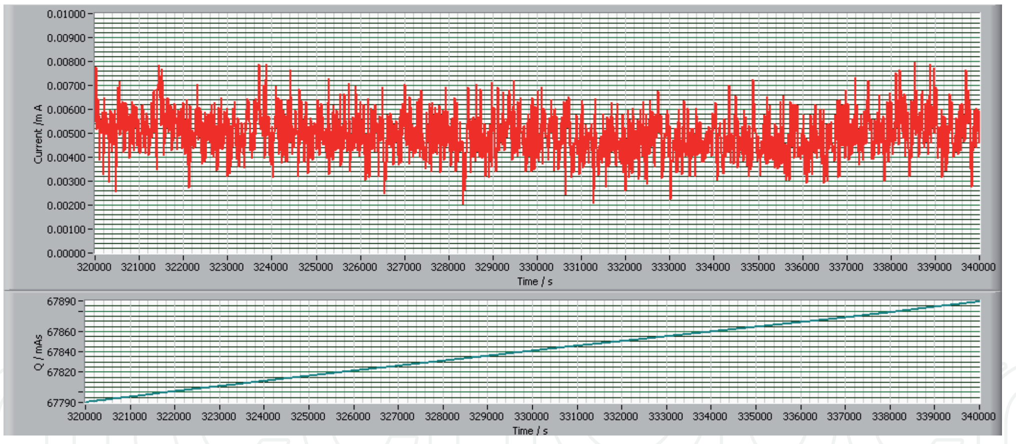

Figure 9.
Supercapacitor leakage current (red line) after 100 hours test. Fluctuations in measurement values arise due to the limited precision of the measurement equipment and noise. The green line depicts charge lost over a 5.5 hours period of time due to leakage current.

supercapacitor with a maximum current limit of 50 mA. The voltage on the supercapacitor and the charge current was recorded at 10 seconds intervals. After 5 hours, the applied voltage was changed from 3.8 to 2.2 V. The discharge of the supercapacitor then started through the power source with the capability to sink current (sink current limit set to 50 mA). This was repeated 7 times. The applied charge to the supercapacitor was also calculated, and is represented by the green line in **Figure 8**.

After seven charge/discharge cycles, a constant 3.8 V was applied to the supercapacitor for the following 30 hours and the leakage current was measured during this period.

From **Figure 9**, the average value of the supercapacitor leakage current is 5 μA. Due to this, the supercapacitor only lost 100 mC or 0.156% of its initial charge during next 5.5 hours. Couple of hours later, this value stabilised below 1 μA.

Since the recommended maximum operating voltage of most microcontrollers and radio chips is 3.6 V, the supercapacitor comes from suppliers already charged to 3.6 V ± 100 mV. It is then soldered onto the sensor module PCB and put into operation.

5. Sensor module's energy conservation

Based on the low leakage current of the supercapacitor, determined in the 100 hour test, it is expected that the sensor module will conserve its energy, for a longer period of time, when not in use. The results displayed in **Figure 10** confirm this assumption. The voltage of the supercapacitor is measured on 10 EnOcean sensor module PCBs assembled almost 3 years ago, before being measured again. These PCBs were then stored and not used. The initial voltage when these samples were first produced is represented by the red dots in **Figure 10**. The supercapacitor voltage of these 10 samples is measured again after 3 years in storage. These results are displayed by the blue dots in the same figure. It is evident that, all 10 supercapacitors lost a similar amount of charge due to their leakage current. However, the measured voltage levels are still significantly high. This suggests that 3 years after production, these sensor modules would still operate normally. In addition to this, as soon as the solar cell is connected, these supercapacitors would begin to recharge to initial voltage levels.

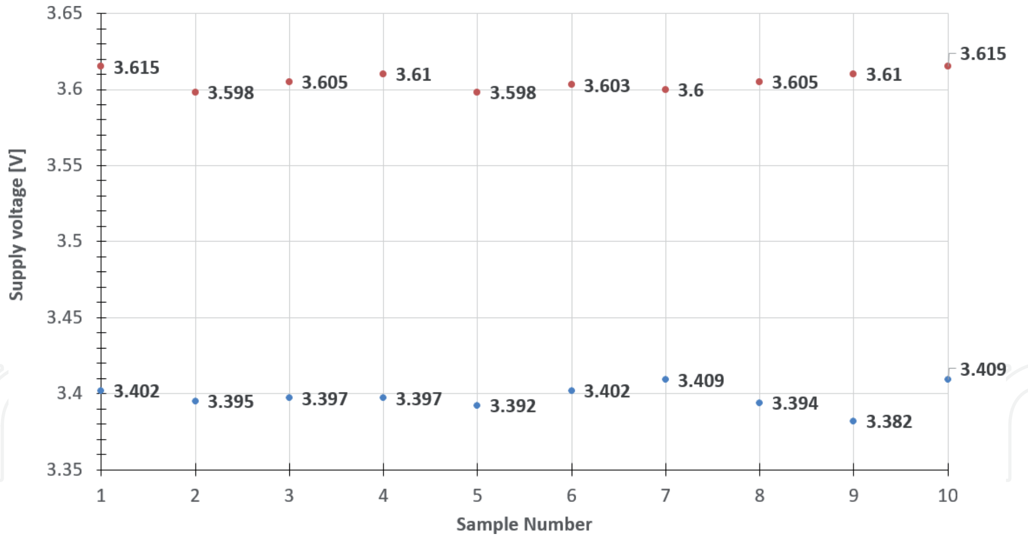

Figure 10.
Measured voltage of the supercapacitors soldered on the developed EnOcean low power, energy harvesting sensor module PCBs at initial assembly (red dots) and after 3 years of no usage (blue dots).

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