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Powering Sigfox Nodes with Harvested Energy

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***Abstract*— Sigfox is one of the popular LPWAN technologies used in the Internet of Things. As in the case of many other wireless protocols, Sigfox nodes are mainly powered with batteries, which leads to important maintenance costs and slows down its acceptance. Enabling such systems to work on harvested energy will facilitate their use and acceptance. We designed and tested a Sigfox node that can be powered by a 1 cm^2 solar cell, opening the door to further optimization in size and costs. Preliminary tests made at the window of one of our office show that one can transmit tens of message per day with that node.**

Keywords—LPWAN; Sigfox; Energy Harvesting; Solar; Wireless; Low Power;

I. INTRODUCTION AND MOTIVATION

According to Market Intelligence firms, billions of IoT nodes will be installed and in use in the years to come. However, there are still important maintenance and ecological issues to deal with. Most IoT nodes are currently powered using batteries (mains in some cases). The use of batteries brings serious limitations. Replacing them is costly and the nodes might not always be accessible. Batteries also come with ecological concerns, since they need to be disposed of when empty. An alternative is to power the nodes with harvested energy. There are currently several efforts to explore how energy scavenging can be applied to different IoT nodes.

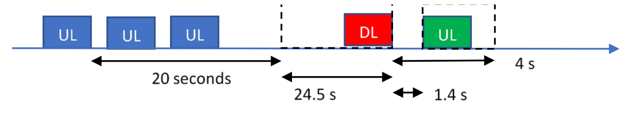
Several energy sources can potentially be used to bring energy autonomy to IoT nodes. TEG, solar, RF, electrodynamic are some examples. Harvesting energy for IoT nodes is not easy to do at competitive price (compared to batteries). The technology requires careful design, that considers the harvesting method, the (extra) associated electronics, the availability of the energy source in the environment of use, outage mitigation, the resulting storage needs and how all these affect the application and cost. Obviously, the power requirements of the load are the starting point, since they determine the amount of energy that is needed and consequently impact the harvester size, power management, storage. For many Low-Power Wide Area Network (LPWAN) nodes, the energy required by the wireless communication is relatively high. It is even dominant in some cases. Typically, tens to hundreds of millijoules are needed to transmit a frame. In comparison, short range communication links such as Bluetooth Smart require tens to hundreds of microjoules for the same payload. This amounts to a factor of 100 to 1000.

The most popular LPWAN systems are currently LoRa/LoRaWAN, Nb-IoT and Sigfox. These systems have different characteristics, which also results in slight differences in their energy requirements [11]. Several papers discuss the use of LoRa/LoRaWAN with harvested energy [7,8,9]. Sigfox has received less attention. In this work, we are mainly concerned with the use of Sigfox.

II. BRIEF DESCRIPTION OF SIGFOX

A detailed description of Sigfox can be found in different documents [5,10]. We will only summarize some important aspects here. Sigfox works in sub-GHz frequency bands (868 MHz in most European countries). It makes use of Ultra Narrow Band technology in order to improve the communication range (ranges of tens of kilometers are possible, depending on the surroundings). Communication between the many nodes and the few base stations is mostly unidirectional. The IoT node takes the initiative in starting the communication, which helps save energy and reduce resource requirements. Bidirectional mode is available, but not often used. For unidirectional (uplink, UL) communication, only the IoT node sends messages to the base station. The modulation in node transmission mode is D-BPSK.

Uplink frame format. 14-29 bytes	Preamble 19 bits	Synch + Header 29 bits	Device ID 32 bits	Payload 0-96 bits	Message Auth. Code 16-40 bits	FCS 16 bits
Downlink frame format. 21-29 bytes	Preamble 91 bits	Synch + Header 13 bits	ECC 32 bits	Payload 0-64 bits	Message Auth. Code 16 bits	FCS 16 bits



Unidirectional exchange. Only the node sends data to the Base Station (BS)
Uplink: same UL frame sent up to 3 times on different random frequencies channels
Bidirectional exchange. BS also sends information (ACK/Command) to the node
Downlink: UL message, then switch to Rx mode to get DL frame from the gateway
The node acknowledges reception of the DL by sending another UL (OOB)

3 different narrow bands frequencies are used to transmit frames in uplink mode, at 100 bit per second.

The bidirectional exchange starts with uplinks. At the end of the UL messages, the receiver of the node is activated to receive a downlink (DL) frame from the base station. That frame is sent at 600 bit per second. An ACK UL frame follows the DL frame of the base station.

The format of a Sigfox message is simple. A maximum payload of 12 bytes is added to the message overhead (about 14 bytes). The overhead includes synchronization and security bits. The downlink message allows at the most 8 bytes in its payload.

Sigfox communication is mostly unidirectional. The total number of downlinks allowed depends on the subscription model. The number of DL is limited to 4 messages per day (best case).

III. RELATED WORK

The authors of [6] have used Sigfox as LPWAN protocol in a sensor application powered by a solar panel. The PV block is relatively large (24 cm^2) [13]. It can be used indoors or outdoors. With 5000 Lux or more, transmissions of Sigfox messages can be made every 5 minutes. The main drawback of this approach is the large solar cell it requires.

Reference [10] reports a theoretical analysis of the energy requirements of Sigfox. Criteria were derived from the specifications and combined with measurements of some modules to estimate the lifetime of a Sigfox node, based on the frequency of data transmission and the energy of the battery used.

An idea of the energy requirements of Sigfox is given in [11]. The authors measured the energy requirements of a recent Sigfox node and compared them to those of LoRa and Nb-IoT. With a payload of 12 bytes and the S2 transceiver of ST Micro, they came to the following results for single transmissions:

For P_{tx} = +14 dBm and Vdd = 3.3 V, E=114 mJ per transmission

For P_{tx} = +14 dBm and Vdd = 1.8 V, E =108 mJ per transmission

For P_{tx} = 0 dBm and Vdd = 3.3 V, E=40 mJ per transmission

For P_{tx} = 0 dBm and Vdd = 1.8 V, E =34 mJ per transmission

These results must then be multiplied by 3 to estimate the energy when data is transmitted 3 times, as is normally the case for the Sigfox protocol. The measurements were made with a stable power supply (no external LDO). When LDOs are used (as in this work), the energy required increases.

In the case of a bidirectional exchange (3 uplink frames, reception of DL from base station, transmission of ACK to base station), the total energy measured approaches 834mJ. An important part of that energy comes from the consumption in Rx mode, while waiting for the downlink frame from the gateway.

The main contribution of this work is the use of a small solar cell (1 cm^2). Such a cell will enable smaller devices, outdoors and possibly indoors.

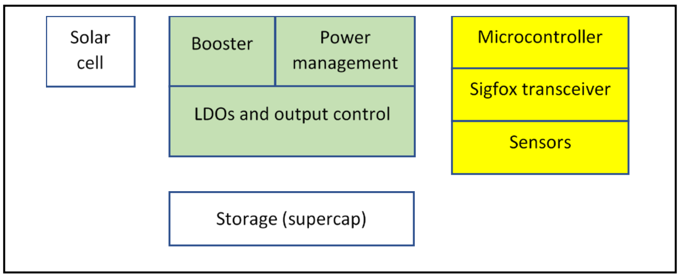
IV. THE AMANDA PROJECT

Some aspects of this work were part of a student's project. It is also related to the EU Amanda project [1] and a ZHAW research project. It follows a pattern whereby ZHAW-InES has been investigating the energy requirements of different wireless technologies and the use of different harvesting methods with the most common IoT technologies.

Amanda is a Horizon2020 research project where HW and SW technologies necessary for the use of energy harvesting in IoT nodes are being developed. "*Its ultimate goal is to develop and validate a cost-attractive next generation Autonomous Smart Sensing Card (ASSC) that will serve multi-sensorial IoT applications for smart living and working environments*" [1]. In this work, we use some of the components from of Amanda partners. The solar cell and power management technologies are from firms that are part of the Amanda consortium. Sigfox is also one the IoT technologies considered by Amanda.

V. DESIGN

The block diagram of the typical IoT wireless system is shown below. The different parts are chosen to work with the design concept as explained later.



A. How the system works (accumulate and release)

In order to run the system and transmit Sigfox frames, one needs hundreds of millijoules (information from energy measurements in [11]). With a small solar cell in an environment where luminosity can be weak, the harvested energy is not suitable to directly power the load. It is important to first accumulate and then release the energy when it is sufficient for the work at hand. That means harvesting enough energy, accumulating it in a storage and then using it when appropriate. Furthermore, the voltage of a small solar cell (0.6 to 1.2 V) is not high enough to supply the load (1.8V- 3.3V required). It is therefore important to step it up.

The energy is accumulated in a supercapacitor. The voltage decreases quickly as it is used. Consequently, the system should work between known voltage points in order to guarantee the supply of the load (sufficient voltage and energy).

The following elements in the design cover the functions described above.

B. The solar cell

The cell used has an active surface of about 1cm2. The device is the ExCellLight EXL1-1V20 module from Lightricity [2]. Some characteristics of the prototype taken from a table in the preliminary datasheet are shown below.

Thanks to its small dimensions the solar cell can fit different types of modules. It can easily be integrated in small or large systems for outdoors or indoors uses. The high efficiency technology used in tis harvester is especially suited for indoors applications, where other technologies require much larger surfaces for the same output. Smaller and larger variations of the cells are in development or in production.

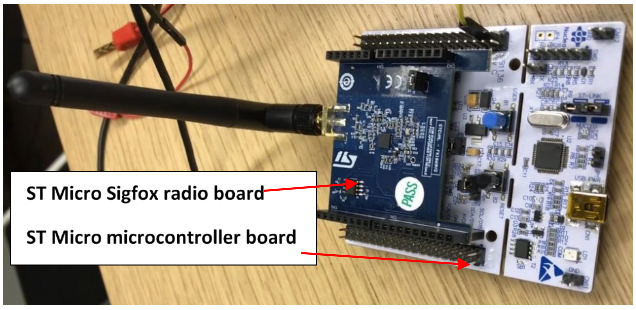
Performance (indication only)	Module
	200 lux white LED spectrum
Size	11.65 x 8.85 x 0.65 mm^3
Active area	98 mm^2
Number of cell(s)	1
Open circuit voltage	1.15 V
Short circuit current	22.7 µA
Operating voltage	1.0 V
Operating current	21.7 µA
Operating power	**21.7 µW**
Power density (active area)	22.1 µW.cm^{-2}

C. Radio

The radio used is the S2 from ST Microelectronics, which allows frames to be sent as required by Sigfox. The device is part of the ST Kit S2-LP-SigFox_DK_1.6.0 [4]

D. Microcontroller

In order to allow fast development and test, an Arduino board equipped with a Cortex M0 of ST Microelectronics was used. ST also provides firmware for the implementation of the Sigfox protocol. That firmware was loaded in the memory of the microcontroller together with the application firmware.



E. The supercapacitor

A 100mF supercapacitor was chosen as storage element. It should provide sufficient energy for the application between the 2 voltage working points, V_a and V_b. That energy is: $E\ (mJ) = 0.5*100\ mF*(V_b^{\ 2} - V_a^2)$

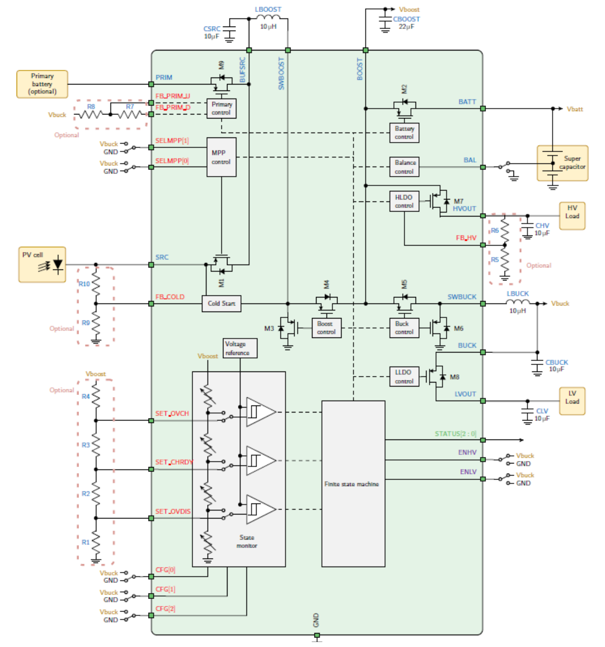
This was calculated to be sufficient for an application that is always restarted from power-off. If it is needed to keep the embedded system under power or save energy for use when there is not enough light, a supercapacitor with higher capacitance should be chosen. The value of the capacitance seriously influences the cold start. The higher that value, the longer it will take to charge the capacitor up to the value needed for the first transmission. This can be critical for small solar cells and for low luminosity environments, especially that efficiency is low when the voltage is low (see measurements).

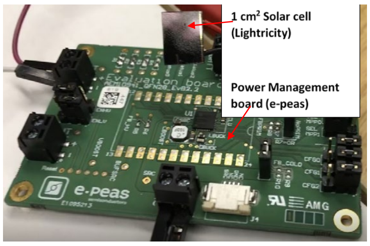
F. Sigfox Base Station (Heliot)

An appropriate base station from an approved operator is needed in order to receive Sigfox frames. The user must have an account on the Sigfox system. For this work, we used the resources of the firm Heliot [14], the Sigfox operator in Switzerland, Lichtenstein and Austria.

G. Power management

The AEM10941 of e-peas [3] is a device that combines booster and power management. A ready to use development kit was enough for our setups and tests. Management of the energy includes charging an external storage, monitoring the voltage of the storage for protection, deciding when to allow or stop the flow of the energy into the load. The device offers the possibility of setting several parameters by using resistances or connecting the appropriate inputs to VDD or GND. LDOs are also integrated into the device to stabilize the voltage of the load. One of the LDO can provide up to 80mA, which easily accommodates the requirements of the Sigfox transmitter at maximum output power (+14dBm in Europe).





The AEM10941 can cold start from 380mV, making it also suitable for use with single solar cells.

VI. RESULTS AND DISCUSSION

Results of measurements are shown in several figures at the end of this document. The reader is advised to refer to them and the associated comments.

The system was placed behind the window of one of our offices and exposed to daylight through that window. Different electrical parameters were recorded over several hours. The energy entering the system (from the solar cell) and the energy consumed by the load can be read from the figures. A luxmeter was also used to record the illuminance. Frames received at the base station were automatically logged. The measurements were carried out in Winterthur, in winter days, (short sunny period). During those days, there was still enough light to allow a large illuminance variation, from 0 Lux to over 40'000 Lux.

For the preliminary measurements reported in this paper, the transmission system was set with a minimal payload of 1 byte and no attempt was made to optimise the firmware (this will be done in the next stage of the work). The system was thus essentially transmitting the communication overhead and 1 information byte.

The power management was set to work with a MPPT factor of 85%. The voltages limits were chosen as follows:

- Power the load when the supercapacitor's voltage reaches 4.4 V during storage charging.
- Disconnected the load when the supercapacitor's voltage discharges down to 3.6 V.
- Regulate the load's voltage at 3.3 V.
- Configure the overload voltage to 4.5 V.

A. *Measuring the harvested energy*

The energy entering the system was monitored by measuring the light illuminance where the solar cell was placed and by measuring the current (I1) and voltage (V1) of the solar cell.

The activation of the MPPT leads to 100ms pulses on the input signal at intervals of about 6 seconds. During those pulses, V1 is nearly equal to the open circuit voltage (Voc) of the solar cell (sometimes greater than 1.2 V).

Input power peaks at about 2.76 mW (measurements of 9-Jan-2020). Towards the end of the day that input power is in the order of a few uWs.

B. *Measuring the stored and used energy*

The energy entering the system is stored in a supercapacitor. The voltage of that element was measured as V3 in one setup. In another setup, the current flowing in (or out of) the supercapacitor was measured (I3). The limitations of our measurement instrument did not allow us to measure both current and voltage of the supercapacitor at the same time.

The energy consumed by the load was also monitored by measuring the current into the load (I2) and the voltage across the load (V2). During transmission, the load current can be as high as 25 mA and the energy consumption over 300 mJ.

A differentiated look at the energy consumption shows that the 3 transmissions of the frame cost about 80*3 = 240 mJ. The extra consumption of 60 mJ comes from the microcontroller (startup, shutdown, communication with radio, … etc.).

Energy is also lost in the LDO. The load is supplied with a constant voltage of 3.3 V, while the supercapacitor voltage varies from 4.4 V down to 3.6 V. A variation that corresponds to 0.5*(4.4*4.4 – 3.6*3.6)*100 = 320 mJ. This value is close to the energy dissipated in the load.

When starting from cold (supercapacitor totally empty), the system requires more time until the voltage at the supercapacitor reaches the value that triggers the embedded system's start. That (system's cold start) is shown in Figure 13.

The system is less efficient when starting from cold (storage empty). It takes several hours until the supercapacitor voltage reaches the required 4.4 V. the energy at that point is then: 4.4*4.4*100*0.5 = 968 mJ

After a transmission, the supercapacitor voltage is at 3.6 V, indicating that the energy in the storage at that moment is 3.6*3.6*100*0.5 = 648 mJ

The measurements and the Sigfox reception logs clearly show that the tens of frames could be transmitted and received.

ACKNOWLEDGMENT

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The work is also partly associated to the Amanda Project sponsored by the Horizon2020 program under the grant agreement ID: 825464. Specifically, the solar cell used is from the firm Lightricity. The power management used is a product of the firm e-peas. Both firms and ZHAW are part of the Amanda Consortium.

We would like to thank the firm Heliot for providing a user account for our works related to Sigfox.

VII. CONCLUSIONS AND FUTURE WORK

This work shows that using a small (but efficient) solar cell with a LPWAN system such as Sigfox is possible. A good power management ensures that energy is harvested early and that the embedded system is kept inactive until enough energy is available. Frames can be sent with maximum output power, enabling a maximum range.

In a next step, the system will be optimized in order to reduce the energy requirements. The payload will be increased to reflect a realistic application. More tests will be made in indoors conditions to evaluate the indoor performances.

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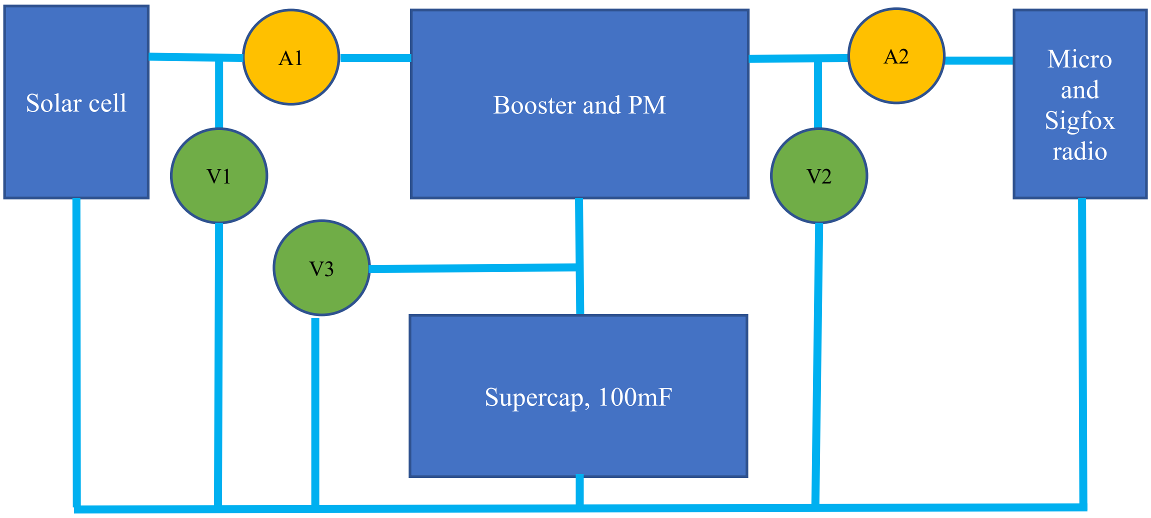


Figure 1. First Setup for measurement. Voltage of supercapacitor is measured. (08-Jan-2020)

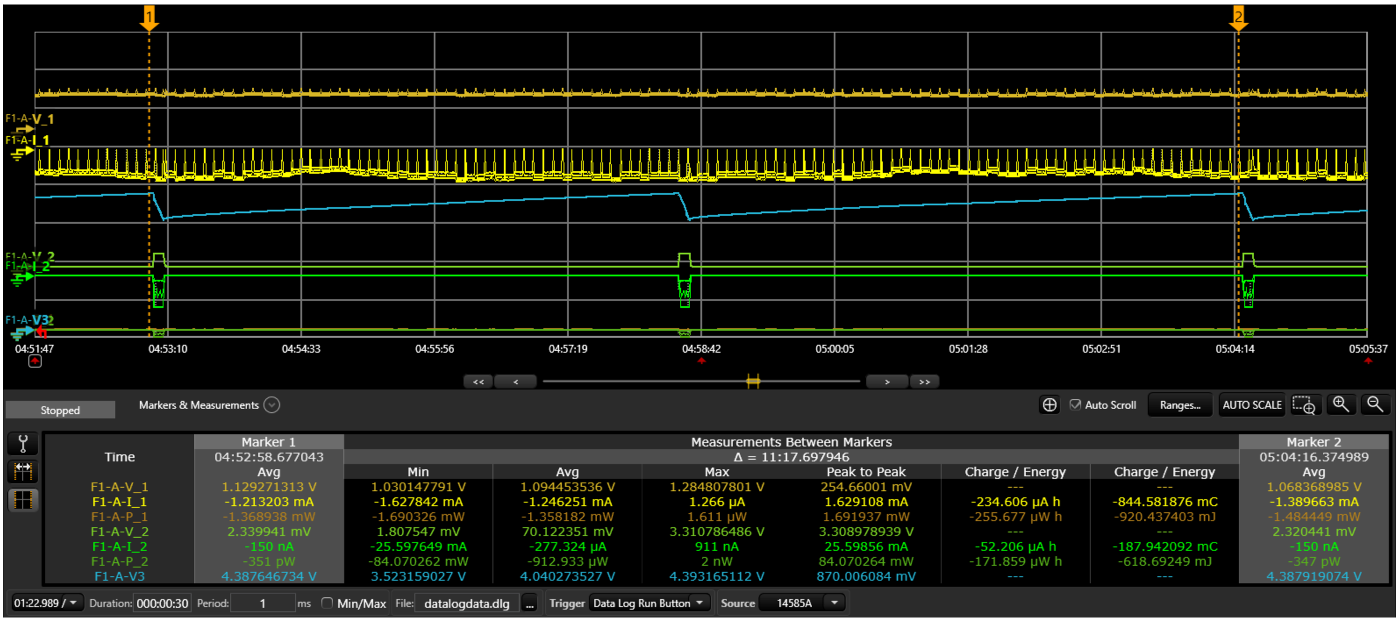
Time	Marker 1	Measurements Between Markers						Marker 2
	39.041434 s	Δ = 07:28:24.084480						07:29:03.125914
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
F1-A-V_1	1.021438975 V	868.695974 mV	1.044393277 V	1.298059464 V	429.363489 mV	---	---	950.378016 mV
F1-A-I_1	-90.009 µA	-2.135155 mA	-432.706 µA	1.552 µA	2.136706 mA	-3.233768 mA h	-11.641564578 C	-40.771 µA
F1-A-P_1	-91.935 µW	-2.218985 mW	-460.65 µW	1.967 µW	2.220952 mW	-3.4426 mW h	-12.393358501 J	-38.745 µW
F1-A-V_2	2.074173 mV	1.679998 mV	138.858061 mV	3.320352793 V	3.318672795 V	---	---	2.212882 mV
F1-A-I_2	-148 nA	-25.652653 mA	-88.442 µA	911 nA	25.653563 mA	-660.96 µA h	-2.379456924 C	-148 nA
F1-A-P_2	-306 pW	-84.252758 mW	-291.159 µW	2 nW	84.252761 mW	-2.175933 mW h	-7.83335764 J	-327 pW
F1-A-V3	3.229660016 V	3.213526726 V	3.950202175 V	4.396764278 V	1.183237553 V	---	---	3.929177321 V

54:06.773 / Duration: 000:00:30 Period: 1 ms ☐ Min/Max File: datalogdata.dlg Trigger Data Log Run Button Source 14585A

Figure 2. More than 7 hours recording of input energy (I1,V1) and used energy (I2,V2). V3 is the supercapacitor voltage. Towards the end of the day, the energy delivered by the solar cell is not enough to reach the 4.4 volts threshold needed to start a transmission.

Sigfox data log shows 21 receptions from our device on 8th January 2020, with the first reception at 09:18

```
Good    N/A    SIGFOX_Switzerland_Heliot    0    1104    08.01.2020 14:38
Good    N/A    SIGFOX_Switzerland_Heliot    0    1103    08.01.2020 14:05
…..
Good    N/A    SIGFOX_Switzerland_Heliot    0    1085    08.01.2020 09:42
Good    N/A    SIGFOX_Switzerland_Heliot    0    1084    08.01.2020 09:18
```

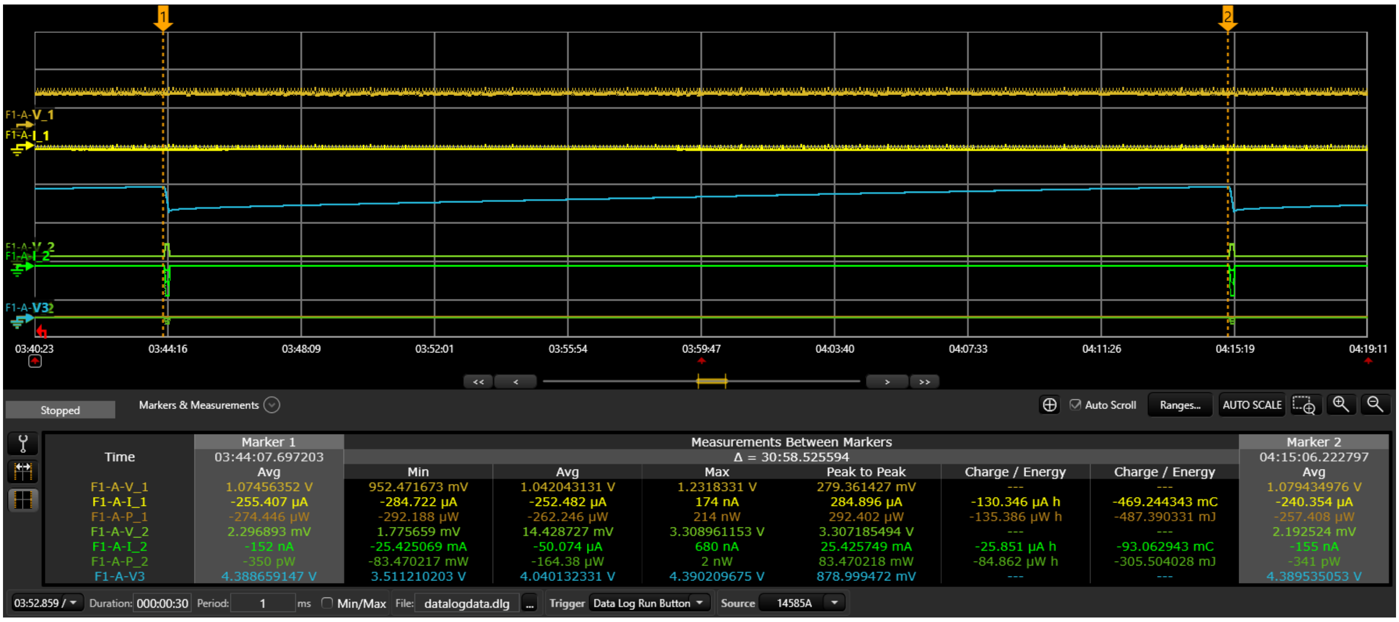


Time	Marker 1	Measurements Between Markers						Marker 2
	04:52:58.677043	Δ = 11:17.697946						05:04:16.374989
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
F1-A-V_1	1.129271313 V	1.030147791 V	1.094453536 V	1.284807801 V	254.66001 mV	---	---	1.068368985 V
F1-A-I_1	-1.213203 mA	-1.627842 mA	-1.246251 mA	1.266 µA	1.629108 mA	-234.606 µA h	-844.581876 mC	-1.389663 mA
F1-A-P_1	-1.368938 mW	-1.690326 mW	-1.358182 mW	1.611 µW	1.691937 mW	-255.677 µW h	-920.437403 mJ	-1.484449 mW
F1-A-V_2	2.339941 mV	1.807547 mV	70.122351 mV	3.310786486 V	3.308978939 V	---	---	2.320441 mV
F1-A-I_2	-150 nA	-25.597649 mA	-277.324 µA	911 nA	25.59856 mA	-52.206 µA h	-187.942092 mC	-150 nA
F1-A-P_2	-351 pW	-84.070262 mW	-912.933 µW	2 nW	84.070264 mW	-171.859 µW h	-618.69249 mJ	-347 pW
F1-A-V3	4.387646734 V	3.523159027 V	4.040273527 V	4.393165112 V	870.006084 mV	---	---	4.387919074 V

01:22.989 / Duration: 000:00:30 Period: 1 ms ☐ Min/Max File: datalogdata.dlg ... Trigger Data Log Run Button Source 14585A

Figure 3: Zoom on 2 harvest/transmit cycles when illuminance high

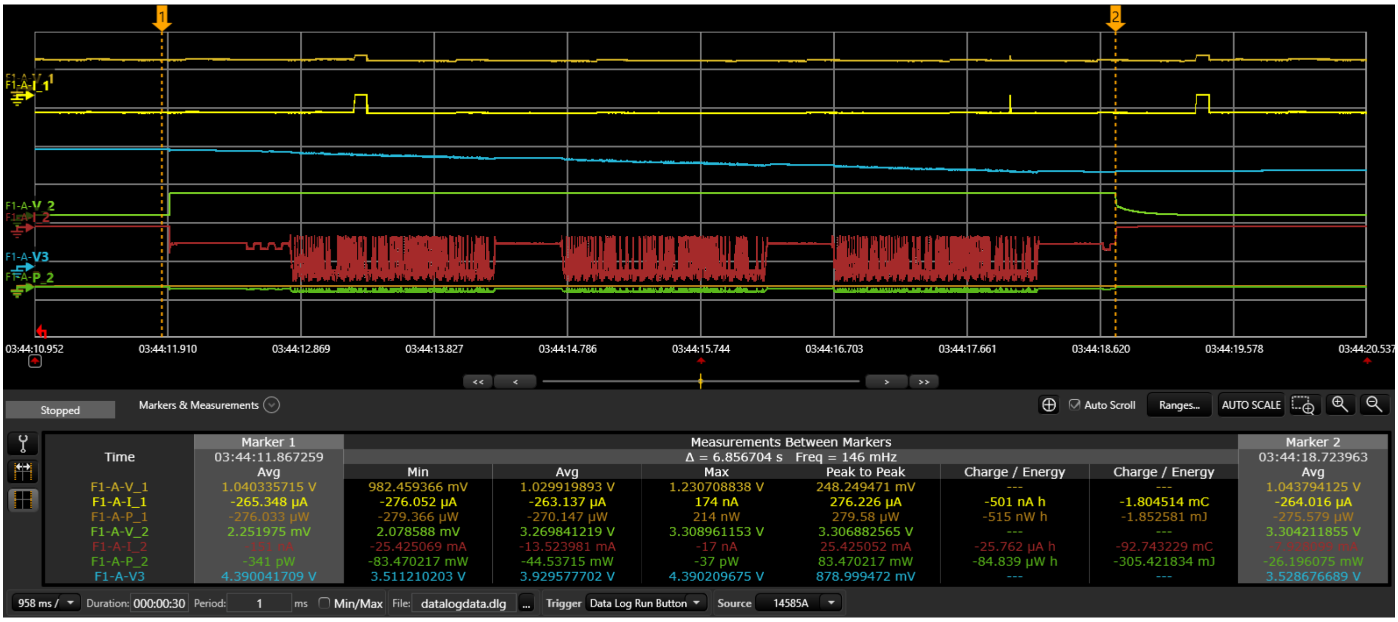
Harvest time for one cycle is 320 s. For the next cycle, it is 343 sec. The variations are related to how much energy is being harvested (depends on illuminance)



Time	Marker 1	Measurements Between Markers						Marker 2
	03:44:07.697203	Δ = 30:58.525594						04:15:06.222797
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
F1-A-V_1	1.07456352 V	952.471673 mV	1.042043131 V	1.2318331 V	279.361427 mV	---	---	1.079434976 V
F1-A-I_1	-255.407 µA	-284.722 µA	-252.482 µA	174 nA	284.896 µA	-130.346 µA h	-469.244343 mC	-240.354 µA
F1-A-P_1	-274.446 µW	-292.188 µW	-262.246 µW	214 nW	292.402 µW	-135.386 µW h	-487.390331 mJ	-257.408 µW
F1-A-V_2	2.296893 mV	1.775659 mV	14.428727 mV	3.308961153 V	3.307185494 V	---	---	2.192524 mV
F1-A-I_2	-152 nA	-25.425069 mA	-50.074 µA	680 nA	25.425749 mA	-25.851 µA h	-93.062943 mC	-155 nA
F1-A-P_2	-350 pW	-83.470217 mW	-164.38 µW	2 nW	83.470218 mW	-84.862 µW h	-305.504028 mJ	-341 pW
F1-A-V3	4.388659147 V	3.511210203 V	4.040132331 V	4.390209675 V	878.999472 mV	---	---	4.389535053 V

03:52.859 / Duration: 000:00:30 Period: 1 ms ☐ Min/Max File: datalogdata.dlg ... Trigger Data Log Run Button Source 14585A

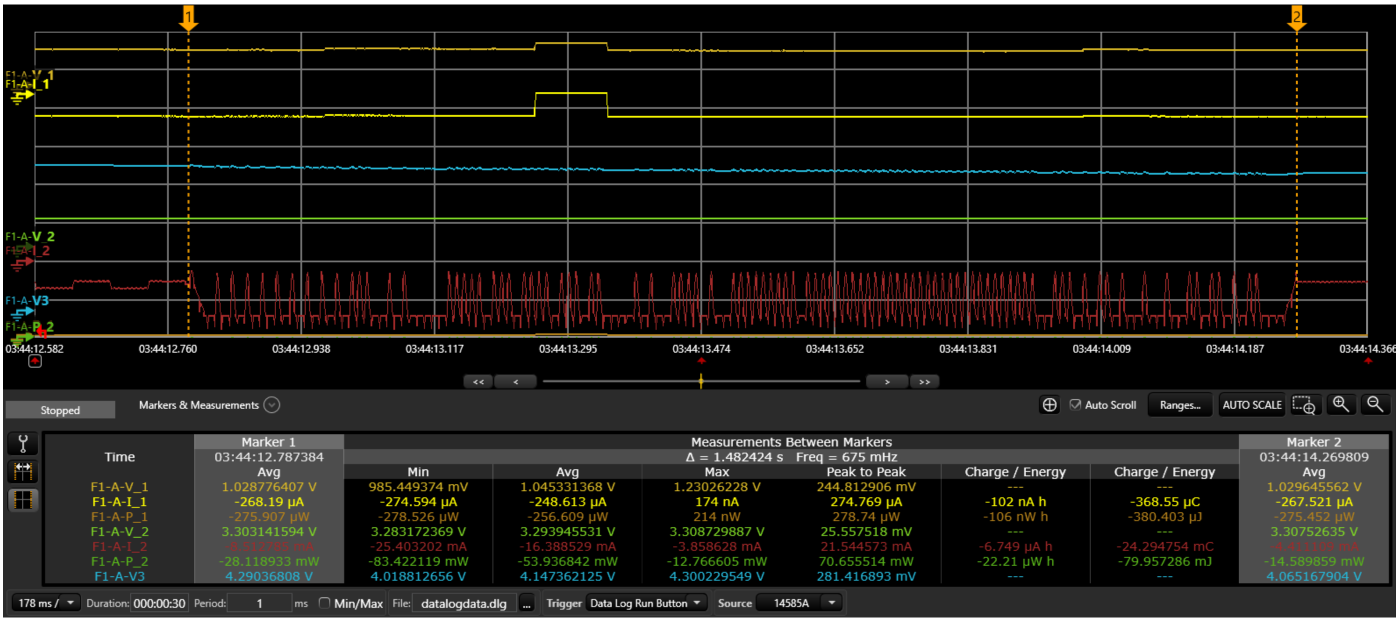
Figure 4. Zoom on a longer harvesting cycle (illuminance low). Harvest cycle duration is about 1846 seconds



Time	Marker 1	Measurements Between Markers						Marker 2
	03:44:11.867259	Δ = 6.856704 s Freq = 146 mHz						03:44:18.723963
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
F1-A-V_1	1.040335715 V	982.459366 mV	1.029919893 V	1.230708838 V	248.249471 mV	---	---	1.043794125 V
F1-A-I_1	-265.348 µA	-276.052 µA	-263.137 µA	174 nA	276.226 µA	-501 nA h	-1.804514 mC	-264.016 µA
F1-A-P_1	-276.033 µW	-279.366 µW	-270.147 µW	214 nW	279.58 µW	-515 nW h	-1.852581 mJ	-275.579 µW
F1-A-V_2	2.251975 mV	2.078588 mV	3.269841219 V	3.308961153 V	3.306882565 V	---	---	3.304211855 V
F1-A-I_2	-151 nA	-25.425069 mA	-13.523981 mA	-17 nA	25.425052 mA	-25.762 µA h	-92.743229 mC	-7.928099 mA
F1-A-P_2	-341 pW	-83.470217 mW	-44.53715 mW	-37 pW	83.470217 mW	-84.839 µW h	-305.421834 mJ	-26.196075 mW
F1-A-V3	4.390041709 V	3.511210203 V	3.929577702 V	4.390209675 V	878.999472 mV	---	---	3.528676689 V

958 ms / Duration: 000:00:30 Period: 1 ms ☐ Min/Max File: datalogdata.dlg ... Trigger Data Log Run Button Source 14585A

Figure 5. Zoom on Sigfox transmission activity (305 mJ needed for the time the embedded System is activated). The same frame is transmitted 3 times. The DC/DC pulse has a duration of about 100 ms and a period of about 6 seconds. Additional energy needed between the transmissions.



Time	Marker 1	Measurements Between Markers						Marker 2
	03:44:12.787384	Δ = 1.482424 s Freq = 675 mHz						03:44:14.269809
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
F1-A-V_1	1.028776407 V	985.449374 mV	1.045331368 V	1.23026228 V	244.812906 mV	---	---	1.029645562 V
F1-A-I_1	-268.19 µA	-274.594 µA	-248.613 µA	174 nA	274.769 µA	-102 nA h	-368.55 µC	-267.521 µA
F1-A-P_1	-275.907 µW	-278.526 µW	-256.609 µW	214 nW	278.74 µW	-106 nW h	-380.403 µJ	-275.452 µW
F1-A-V_2	3.303141594 V	3.283172369 V	3.293945531 V	3.308729887 V	25.557518 mV	---	---	3.30752635 V
F1-A-I_2	-8.512785 mA	-25.403202 mA	-16.388529 mA	-3.858628 mA	21.544573 mA	-6.749 µA h	-24.294754 mC	-4.411109 mA
F1-A-P_2	-28.118933 mW	-83.422119 mW	-53.936842 mW	-12.766605 mW	70.655514 mW	-22.21 µW h	-79.957286 mJ	-14.589859 mW
F1-A-V3	4.29036808 V	4.018812656 V	4.147362125 V	4.300229549 V	281.416893 mV	---	---	4.065167904 V

178 ms / Duration: 000:00:30 Period: 1 ms ☐ Min/Max File: datalogdata.dlg ... Trigger Data Log Run Button Source 14585A

Figure 6. Zoom on one Sigfox transmission. 1.48 sec and 80 mJ. Details of the transmission can be seen.

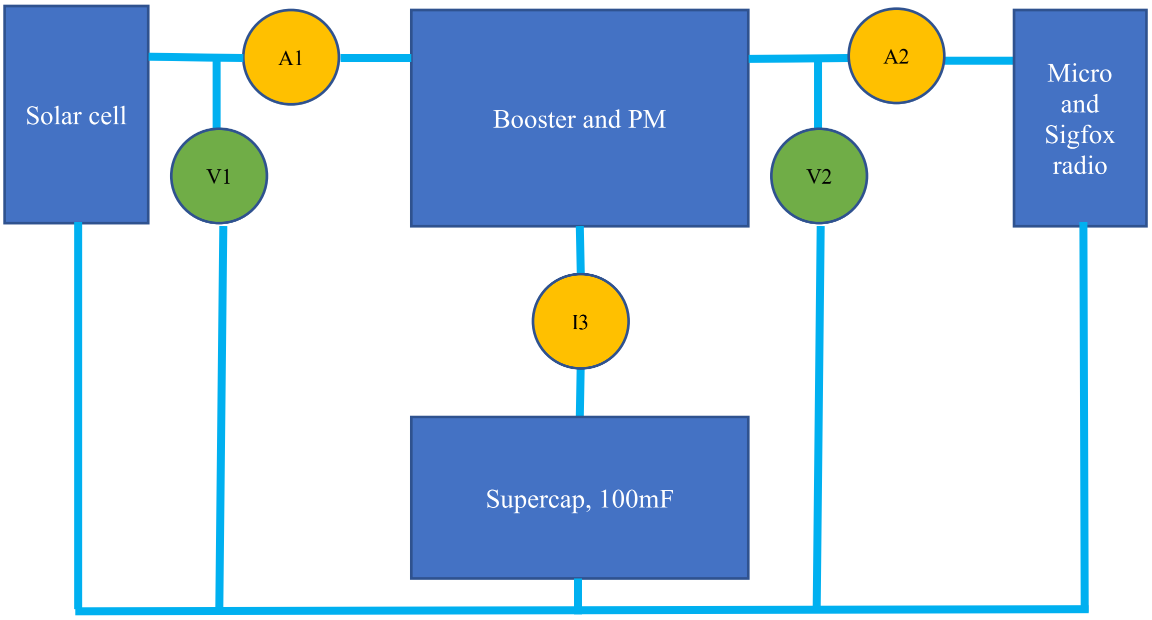
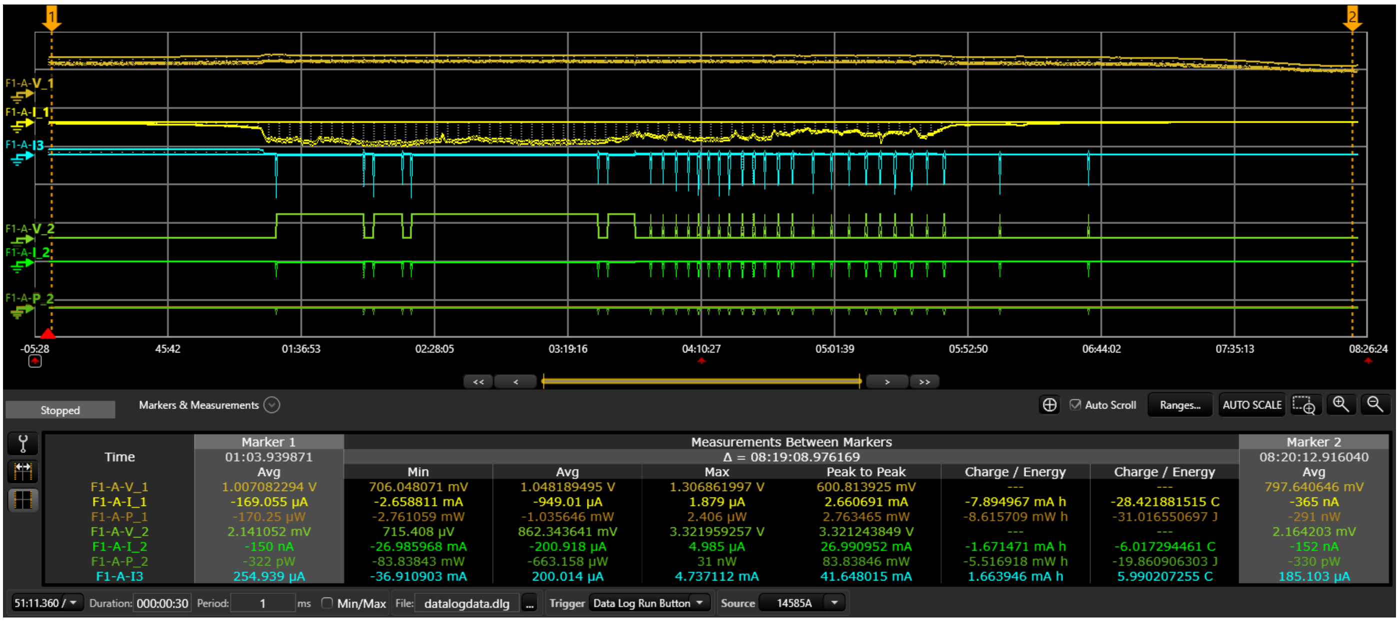


Figure 7. Second setup for measurement. Current through the supercapacitor is measured. (09-Jan-2020)



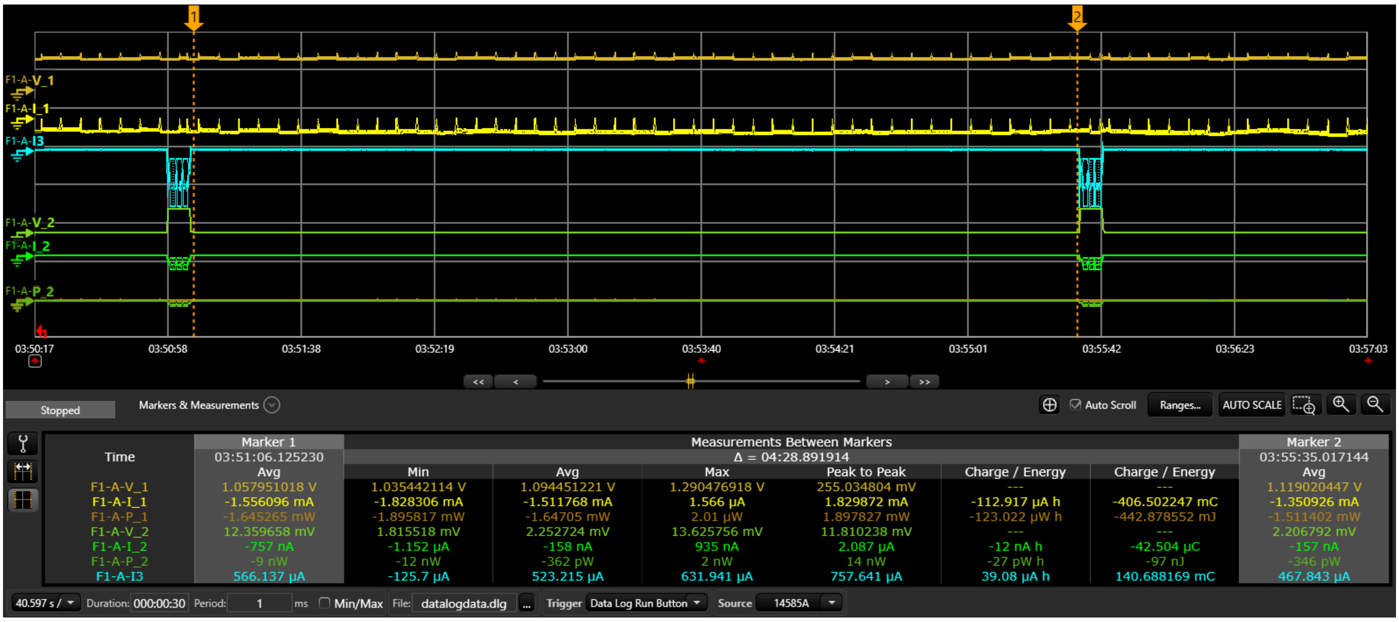
Time	Marker 1	Measurements Between Markers						Marker 2
	01:03.939871	Δ = 08:19:08.976169						08:20:12.916040
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
F1-A-V_1	1.007082294 V	706.048071 mV	1.048189495 V	1.306861997 V	600.813925 mV	---	---	797.640646 mV
F1-A-I_1	-169.055 µA	-2.658811 mA	-949.01 µA	1.879 µA	2.660691 mA	-7.894967 mA h	-28.421881515 C	-365 nA
F1-A-P_1	-170.25 µW	-2.761059 mW	-1.035646 mW	2.406 µW	2.763465 mW	-8.615709 mW h	-31.016550697 J	-291 nW
F1-A-V_2	2.141052 mV	715.408 µV	862.343641 mV	3.321959257 V	3.321243849 V	---	---	2.164203 mV
F1-A-I_2	-150 nA	-26.985968 mA	-200.918 µA	4.985 µA	26.990952 mA	-1.671471 mA h	-6.017294461 C	-152 nA
F1-A-P_2	-322 pW	-83.83843 mW	-663.158 µW	31 nW	83.83846 mW	-5.516918 mW h	-19.860906303 J	-330 pW
F1-A-I3	254.939 µA	-36.910903 mA	200.014 µA	4.737112 mA	41.648015 mA	1.663946 mA h	5.990207255 C	185.103 µA

51:11.360 / Duration: 000:00:30 Period: 1 ms ☐ Min/Max File: datalogdata.dlg Trigger Data Log Run Button Source 14585A

Figure 8. measurements over 8 hours

Sigfox data log shows 31 receptions from our device on 9th January 2020, with the first reception at 09:47

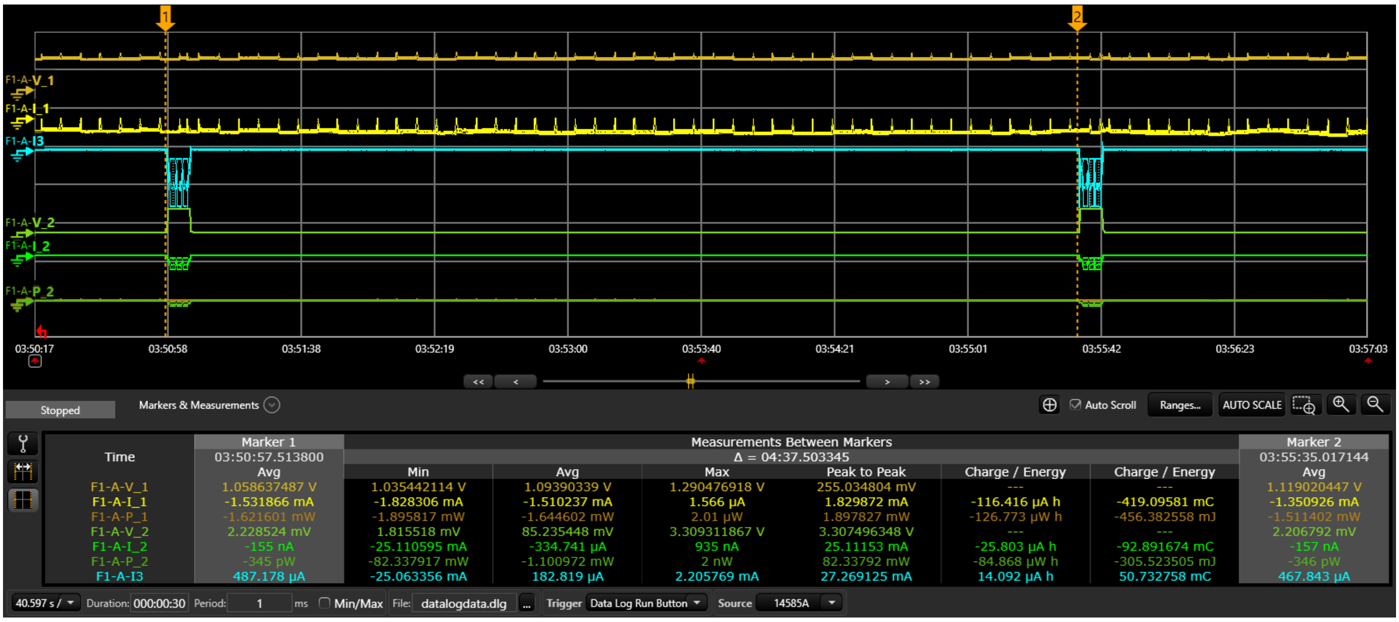
Good	N/A	SIGFOX_Switzerland_Heliot	0	1135	09.01.2020 14:59
Good	N/A	SIGFOX_Switzerland_Heliot	0	1134	09.01.2020 14:25
…..					
Good	N/A	SIGFOX_Switzerland_Heliot	0	1106	09.01.2020 10:21
Good	N/A	SIGFOX_Switzerland_Heliot	0	1105	09.01.2020 09:47



Time	Marker 1	Measurements Between Markers						Marker 2
	03:51:06.125230	Δ = 04:28.891914						03:55:35.017144
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
F1-A-V_1	1.057951018 V	1.035442114 V	1.094451221 V	1.290476918 V	255.034804 mV	---	---	1.119020447 V
F1-A-I_1	-1.556096 mA	-1.828306 mA	-1.511768 mA	1.566 µA	1.829872 mA	-112.917 µA h	-406.502247 mC	-1.350926 mA
F1-A-P_1	-1.645265 mW	-1.895817 mW	-1.64705 mW	2.01 µW	1.897827 mW	-123.022 µW h	-442.878552 mJ	-1.511402 mW
F1-A-V_2	12.359658 mV	1.815518 mV	2.252724 mV	13.625756 mV	11.810238 mV	---	---	2.206792 mV
F1-A-I_2	-757 nA	-1.152 µA	-158 nA	935 nA	2.087 µA	-12 nA h	-42.504 µC	-157 nA
F1-A-P_2	-9 nW	-12 nW	-362 pW	2 nW	14 nW	-27 pW h	-97 nJ	-346 pW
F1-A-I3	566.137 µA	-125.7 µA	523.215 µA	631.941 µA	757.641 µA	39.08 µA h	140.688169 mC	467.843 µA

40.597 s / Duration: 000:00:30 Period: 1 ms ☐ Min/Max File: datalogdata.dlg ... Trigger Data Log Run Button Source 14585A

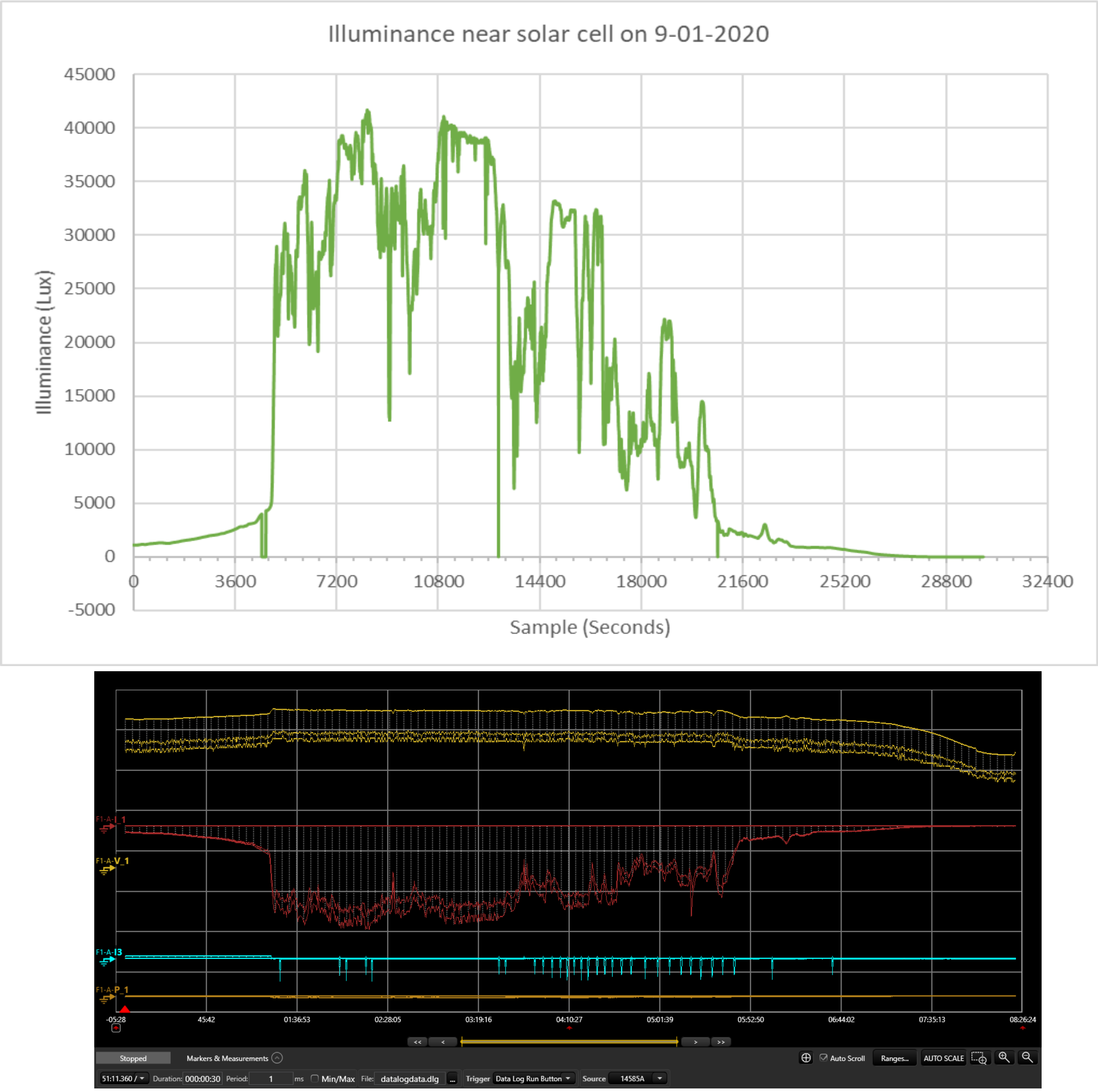
Figure 9. The current flowing through the supercapacitor while harvesting has peaks at +631uA (average in period is +523uA). The storage is being charged.



Time	Marker 1	Measurements Between Markers						Marker 2
	03:50:57.513800	Δ = 04:37.503345						03:55:35.017144
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
F1-A-V_1	1.058637487 V	1.035442114 V	1.09390339 V	1.290476918 V	255.034804 mV	---	---	1.119020447 V
F1-A-I_1	-1.531866 mA	-1.828306 mA	-1.510237 mA	1.566 µA	1.829872 mA	-116.416 µA h	-419.09581 mC	-1.350926 mA
F1-A-P_1	-1.621601 mW	-1.895817 mW	-1.644602 mW	2.01 µW	1.897827 mW	-126.773 µW h	-456.382558 mJ	-1.511402 mW
F1-A-V_2	2.228524 mV	1.815518 mV	85.235448 mV	3.309311867 V	3.307496348 V	---	---	2.206792 mV
F1-A-I_2	-155 nA	-25.110595 mA	-334.741 µA	935 nA	25.11153 mA	-25.803 µA h	-92.891674 mC	-157 nA
F1-A-P_2	-345 pW	-82.337917 mW	-1.100972 mW	2 nW	82.33792 mW	-84.868 µW h	-305.523505 mJ	-346 pW
F1-A-I3	487.178 µA	-25.063356 mA	182.819 µA	2.205769 mA	27.269125 mA	14.092 µA h	50.732758 mC	467.843 µA

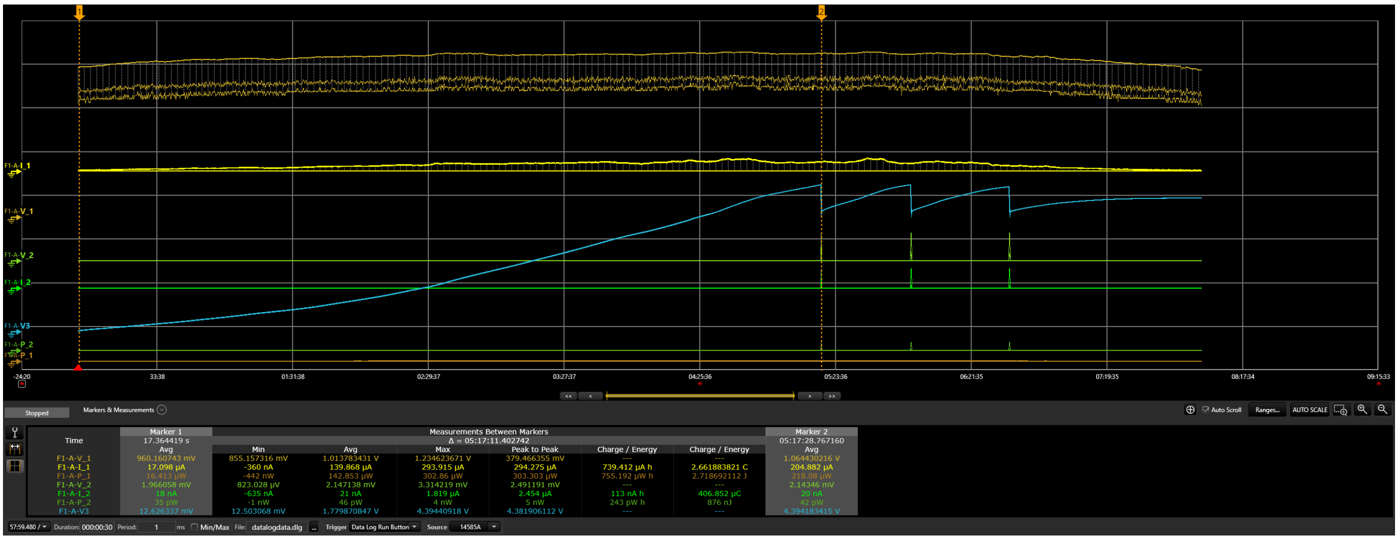
40.597 s / Duration: 000:00:30 Period: 1 ms ☐ Min/Max File: datalogdata.dlg ... Trigger Data Log Run Button Source 14585A

Figure 10. Current through the supercapacitor while discharging (transmitting) has peaks at -25 mA. The storage is being discharged and the energy used to power the load.



51:11.360 /
Duration: 000:00:30
Period: 1 ms
☐ Min/Max
File: datalogdata.dlg
Trigger Data Log Run Button
Source 14585A

Figure 11. Illuminance and energy measurements. The illuminance measurements give an idea of the light conditions during the day, in the area where the solar cell is placed. One can see that the amount of energy at the output of the solar cell (P1) follows the illuminance. The frequency of frame transmission should increase with the light intensity. However, a firmware error prevents many frames to be transmitted quickly when the system harvests a lot of energy.

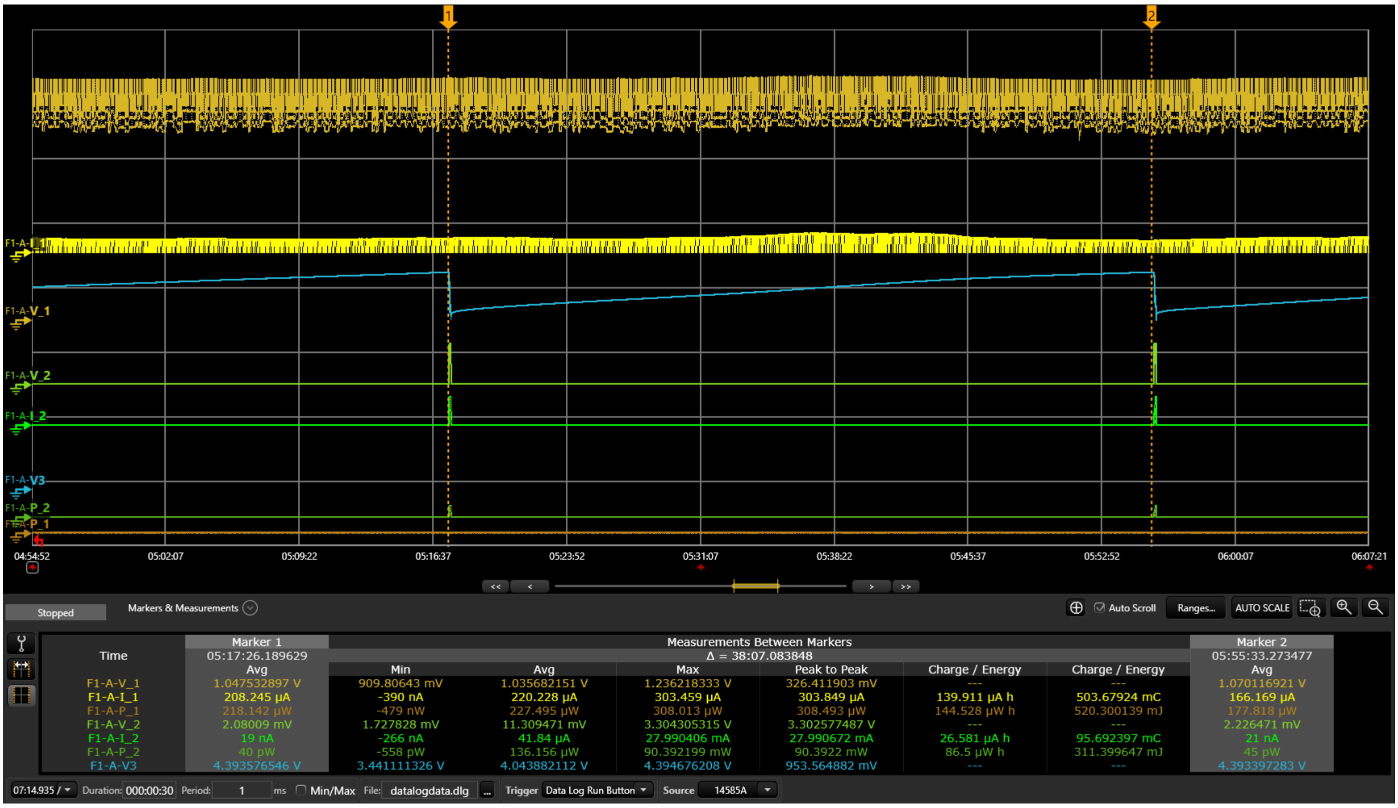


Time	Marker 1	Measurements Between Markers						Marker 2
	17.364419 s	Δ = 05:17:11.402742						05:17:28.767160
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
F1-A-V_1	960.160743 mV	855.157316 mV	1.013783431 V	1.234623671 V	379.466355 mV	---	---	1.064430216 V
F1-A-I_1	17.098 µA	-360 nA	139.868 µA	293.915 µA	294.275 µA	739.412 µA h	2.661883821 C	204.882 µA
F1-A-P_1	16.413 µW	-442 nW	142.853 µW	302.86 µW	303.303 µW	755.192 µW h	2.718692112 J	218.08 µW
F1-A-V_2	1.966058 mV	823.028 µV	2.147138 mV	3.314219 mV	2.491191 mV	---	---	2.14346 mV
F1-A-I_2	18 nA	-635 nA	21 nA	1.819 µA	2.454 µA	113 nA h	406.852 µC	20 nA
F1-A-P_2	35 pW	-1 nW	46 pW	4 nW	5 nW	243 pW h	876 nJ	42 pW
F1-A-V3	12.626337 mV	12.503068 mV	1.779870847 V	4.39440918 V	4.381906112 V	---	---	4.394183415 V

57:59.480 / Duration: 000:00:30 Period: 1 ms ☐ Min/Max File: datalogdata.dlg Trigger Data Log Run Button Source 14585A

Figure 12. Cold start. Storage is empty at start. Several hours are needed to reach the required voltage level of 4.4 V

Measurements done on 5 December 2019. Started around 9:00 in the morning with an empty supercapacitor. First charge of the supercapacitor took more than 4 hours (the sun intensity in the morning is low) and required more than 2.7 joules at the input. The energy in the storage at trigger point is 0.5*100mF*4.4V*4.4V = 968 mJ. This shows an overall efficiency at startup of about 35% The efficiency is better at higher voltages.



Time	Marker 1	Measurements Between Markers						Marker 2
	05:17:26.189629	Δ = 38:07.083848						05:55:33.273477
	Avg	Min	Avg	Max	Peak to Peak	Charge / Energy	Charge / Energy	Avg
F1-A-V_1	1.047532897 V	909.80643 mV	1.035682151 V	1.236218333 V	326.411903 mV	---	---	1.070116921 V
F1-A-I_1	208.245 µA	-390 nA	220.228 µA	303.459 µA	303.849 µA	139.911 µA h	503.67924 mC	166.169 µA
F1-A-P_1	218.142 µW	-479 nW	227.495 µW	308.013 µW	308.493 µW	144.528 µW h	520.300139 mJ	177.818 µW
F1-A-V_2	2.08009 mV	1.727828 mV	11.309471 mV	3.304305315 V	3.302577487 V	---	---	2.226471 mV
F1-A-I_2	19 nA	-266 nA	41.84 µA	27.990406 mA	27.990672 mA	26.581 µA h	95.692397 mC	21 nA
F1-A-P_2	40 pW	-558 pW	136.156 µW	90.392199 mW	90.3922 mW	86.5 µW h	311.399647 mJ	45 pW
F1-A-V3	4.393576546 V	3.441111326 V	4.043882112 V	4.394676208 V	953.564882 mV	---	---	4.393397283 V

07:14.935 / Duration: 000:00:30 Period: 1 ms ☐ Min/Max File: datalogdata.dlg Trigger Data Log Run Button Source 14585A

Figure 13. Efficiency of whole system during charge discharge. The efficiency is affected by several elements

Here, the embedded system activity (including transmission of Sigfox message) costs about 310 mJ.
38 minutes are needed to recharge the supercapacitor to the level needed for the next transmission (320 mJ from 3.6 V to 4.4 V). The energy input during the recharge of the supercapacitor is 520 mJ in this case. Part of the energy is certainly lost in the supercapacitor. The overall efficiency is: 100% * 320/520 = 62%