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 cm² 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, ten 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.
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 cm²) [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 Ptx = +14 dBm and Vdd = 1.8 V, E = 108 mJ per transmission
- For Ptx = 0 dBm and Vdd = 1.8 V, E = 34 mJ per transmission
- For Ptx = 0 dBm and Vdd = 3.3 V, E = 40 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 834 mJ. 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 cm²). 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 of 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-I1V20 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 this 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.

\[
\text{E (mJ) = 0.5*100 mF*(V_b^2 - V_a^2)}
\]

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).

\section*{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.

\section*{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.
REFERENCES

[2] Lightricity:  https://lightricity.co.uk/
1cm² Solar cell. ExCellLight EXL1-1V20 module prototype preliminary datasheet. Contact Lightricity if datasheet not available on web site.
[4] ST Sigfox kit:
https://www.mdpi.com/1424-8220/19/3/681
[14] Heliot. Sigfox operator in Switzerland:
https://www.heliotgroup.com/switzerland/
Figure 1. First Setup for measurement. Voltage of supercapacitor is measured. (08-Jan-2020)

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

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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).

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

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

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)

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

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<td>09:47</td>
<td>SIGFOX_Switzerland_Heliot</td>
<td>0</td>
<td>1105</td>
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</table>
Figure 9. The current flowing through the supercapacitor while harvesting has peaks at $+631\mu A$ (average in period is $+523\mu A$). The storage is being charged.

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.
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.
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 $0.5 \times 100 \text{mF} \times 4.4 \text{V} \times 4.4 \text{V} = 968 \text{ mJ}$. This shows an overall efficiency at startup of about 35%. The efficiency is better at higher voltages.

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: $100\% \times \frac{320}{520} = 62\%$