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Wireless sensing using LEDs as very low-cost energy harvesters

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Abstract—Although energy harvesting has been around for years, it still struggles to find widespread acceptance. One reason is the cost of harvesters and the associated electronics. In this work, we use LEDs as cost effective energy harvesters. Their production in very large quantities has made them price competitive. They can also be easily integrated in production flows. Despite their inefficiency when used as harvesters, they can be an alternative in applications where enough light is available. With 3 to 5 LEDs, we can accumulate enough energy to send messages with proprietary or Bluetooth Smart compatible frames.

Keywords—Light Emitting Diodes; Energy Harvesting; wireless systems; power management; Proprietary wireless;Ble; Bluetooth Smart;

I. INTRODUCTION

Energy harvesting has been around for several years. Despite its promises, this method of bringing energy autonomy to wireless embedded systems has not yet achieved widespread acceptance. There are several reasons to this. One of them is the cost of products that integrate energy harvesters, especially when compared to equivalent products powered with traditional batteries. A good part of this cost can be traced back to harvesters and to the electronics associated with them. The need for special packages and the consequences at production also induce extra costs.

Fig.1. Shows typical parts found in a wireless system powered by an energy harvester. It can be seen that near the harvester (element 1) several other elements could be needed (elements 2,3,4). The complexity of each of these elements depends on the application, the type of harvester, the load that needs to be powered [3]. A reduction in the costs of systems powered by energy harvesters should address those points. In this work we concentrate on systems that are operated in the presence of enough light.

Solar cells are the harvester of choice in environments where there is sufficient light. They are available in several forms and types [9,10,11]. Some cells are optimized for indoors applications while others perform at the best when outside. The larger the cell, the more energy one can harvest. But larger cells are also more expensive. In general, solar cells cost more than traditional batteries. In WPAN, it is best to keep them small. However, there are limits on how small one can get and still remain cost effective.

There are use cases where very little energy is needed. A very small solar cell would be good enough. The reduced power requirement might result from the duty cycle of the activities of the embedded system or from the low energy requirements of the load. This is often the case when the sensing frequency of a measurement system is very low (applications where parameters to measure change slowly). This is true for a weather station placed in a garden. Delivering data every 10-15 minutes during the day will be good enough. It is also the case when monitoring certain parameters in an office, a public place or a factory floor, where enough light is always needed to carry out regular activities. In such situations, the optimal solar cell will be very small. But these cells do not exist at the required costs. As an alternative, we turned to LEDs as cost effective means of powering wireless sensors. The data generated can be sent to a computer, a smartphone or a gateway for Internet of Things related applications.

The use of LEDs has the following advantages:

- LEDs are available at low costs. They also fit very well with actual product manufacturing thus eliminating the problems and costs associated with special packages. These factors make the system cost competitive when used in environments where there is sufficient light.

- LEDs can be very small. If few of them are used, the product has a better size reduction potential than an equivalent powered by the popular CR2032 battery (often used in wireless embedded systems).
- Although batteries have much more energy available, they are guaranteed only for a certain number of years. A solution with LEDs can last longer and will outlive the battery solution.
- Disposing of products with batteries is often an issue. This is less problematic with LEDs.

II. LEDS AS SOLAR CELLS

LEDs are overwhelmingly used in order to produce light. The last years have seen an amazing increase in this trend, with LEDs replacing traditional light sources. The introduction of favorable legislation in certain countries has accelerated this trend. As a result there are important efforts to improve these components and to reduce their costs. A quick search on Internet shows that prices well below $0.05 per unit are not uncommon for 100K quantities of standard small red LEDs. This price goes down as quantities increase. It will take several LEDs to match the price of a CR2032 with soldering holder.

Because of the way they are made, LEDs can also sense light. They have been used as sensors, replacing photodiodes in certain applications [6,7,8]. The physics background to this can be found in many documents [4]. The possibility of using one device alternatively to emit and to sense light has also been investigated and reported [5].

A more unusual use of LEDs is that of energy harvester. In the presence of sufficient light, the energy generated can be used to power a small load. There have been reports of such uses, for instance to act as a kind of RFID sensor [2]. As far as we know, there has been no report of using LEDs to power wireless sensors, let alone sensors compatible with Bluetooth Smart.

When used for sensing (and for delivering energy), LEDs will respond to light with a wavelength smaller or near to the wavelength of the light they generate when configured as light emitting diode. For instance, a red LED will respond to red, yellow, green light, but not to infrared signals.

III. THE DESIGN

The block diagram of the system that we built can be taken from Fig.1, keeping elements 1,2,3,5,6,7. Some of the circuits used are application specific and cannot be found on the market. The system was built as to allow us to experiment with different combinations of the LEDs. They can be connected in parallel or in series depending on the environment and use case.

We began by making a selection of diodes. Several LEDS were tested in different light conditions and the energy delivered measured. One type was selected for the prototype system. The appropriate electronics was built, in order to allow the energy to be accumulated and then released when the right amount is reached. Some of the important design elements are listed below.

1) LEDs

The LEDs should be chosen to fit the light that is available (spectral contents). For outdoors applications, there is enough energy in the different spectral bands. For applications with artificial light, this consideration is critical. It should also be remembered that because of the focusing optics, the orientation of the LED will play a role. Care should be taken not to subject the harvesters to intense light. There is the danger of increasing their temperature, affecting their performance or even destroying them.

2) Electronics to allow accumulation of the energy

LEDs are not primarily built for harvesting. Therefore, they generate very small currents (a few µA to tens of nA in our case). Because of the small current generated, the influence of the load is very important. For instance, while measuring the harvested voltage, a 10MOhms oscilloscope probe can already be enough to strongly impact (or even prevent) charging the capacitor (storage) in indoors light conditions. We used a low current isolation circuit to separate the load from the main load during the energy accumulation process. When the needed voltage is reached, the system automatically connects the load to the storage in order to power it on and to perform the required tasks.

3) Appropriate storage

We used different capacitors, depending on the amount of energy needed to power the embedded system. Since the radio is the part that consumes the most energy in our case, the format and length of the wireless frame should be taken into account. The energy requirements of the sensor should also be added. The capacitor is a low leakage element, in order to reduce the losses. If the leakage is too high, it will not be possible to accumulate energy. In that case, one will need a higher light intensity or more LEDs in parallel.

4) Controller and radio

These elements are ASICS. They were optimized to allow the system to start and run with a minimum amount of energy. This includes calibration, the configuration activities for the radio, the sensing and the sending of data. The radio emulates the Link layer of the Ble standard to allow compatible frames to be sent to Ble devices. The firmware was kept very simple (and low power) since data is only sent in ADV mode. The structure of the ADV frame allows compatibility with previous works done at ZHAW-InES [1]

IV. TESTS AND RESULTS

The setup for measuring the harvester is shown in Fig. 2. Fig. 3 shows the harvester with several diodes for tests.

The setup consists of a light source, a luxmeter, the LEDs board. The voltage at the capacitor during the harvesting is measured using an active probe with very high impedance. It is important to orientate the LEDs properly, because of their optics. One can also use LEDs that have a wider angle.

Fig. 4 shows the results of the measurements with diodes connected one after the other in series and the voltage at the capacitor storage measured. With 4 diodes, more than 5 volts can be reached in less than 600 seconds.

Fig. 5 shows the voltage if 3 diodes are connected in series to start with. It can be seen that the voltage at the storage reaches 3.8 volts after about 300 seconds.

We experimented with 2 different wireless systems based on the same hardware. Only the software needed to be modified.

1) *Proprietary wireless system*

In the first case, the radio was programmed in a proprietary mode. This is the mode requiring the smallest amount of energy. The payload was kept minimal and date transmitted as fast as possible. In that configuration, the energy consumption was less than 7µJ. The small amount of energy means that one could work with smaller storage elements. One could also send more frames per time unit or work with less light. The disadvantage is that a proprietary radio is required to receive the signal. In Fig. 10 it can be seen that with 4 LEDs and 250 lux, one harvests enough energy to send proprietary messages after 76 seconds. At 1000 lux, the message frequency increases to 1 after 23 seconds (Fig. 11)

2) *Ble compatible ADV frames*

In the second case, the frames used are compatible with Bluetooth Smart and can therefore be received on a smartphone or any other device equipped with that wireless standard. The energy consumption is higher and a larger storage capacitor is required. The system will also need more light. Fig. 6 shows the energy consumption of the wireless system in the best case of a low constant voltage (about 2 volts).

The voltage delivered by the storage element to the load is not really constant. The storage element is a capacitor. This means that the system must be so designed that the capacitor has enough energy for the load as it discharges. The lowest Vdd should not be lower that the VDDmin of the embedded system. Consequently, the energy consumption of the whole system is higher, than the best case. More energy must therefore be harvested.

With 4.5v on 1µF, the accumulated energy is about 10µJ. That is 8µJ available between 4.5v and 2v. This was enough to transmit a proprietary frame. But this is not enough for the Ble frames. Increasing the luminosity to 1000 lux allowed us to harvest faster. This will be good enough in some buildings.

For Ble compatible frames, more energy was needed in the storage. We used a 10µF capacitor. Loading the capacitor at 4.5 volts will yield about 100µJ. Of this energy, 80µJ can be used between 4.5v and 2v. This is enough to send 1 to 3 ADV frames.

Fig. 7 shows the energy consumption of the system when the energy is not sufficient. Here in the case of Ble. It can be clearly seen that the voltage breaks down after the radio starts sending. The frame is only partly transmitted, resulting in a CRC error.

Fig. 8 shows the whole system consumption when one Ble frame is properly transmitted.

Using the 10µF capacitor and working at 1000 lux, it was possible to send a message after 114 seconds (Fig. 9).

V. COSTS

For outdoor applications, 4 diodes connected in series will be enough. Their cost is well below that of a CR2032 with battery holder. However, the circuit also needs a low power isolation circuit to allow energy to be stored. We estimate that costs around $1 with the EH and associated electronics are possible, making the system competitive for the kind of applications described here.

VI. CONCLUSIONS

We demonstrated a very low-cost battery-less node powered by LEDs. The system has the potential to compete in price with battery based systems. It can last longer, (beyond the guaranteed lifecycle of batteries). It is smaller (compared to a standard system based on a CR2032) and more robust. As disadvantage, it can be used only where there is sufficient light (typically 600 lux or more with the appropriate spectral content). It is also for applications where communication is only needed at intervals of tens of seconds, so as to allow the accumulation of enough energy.

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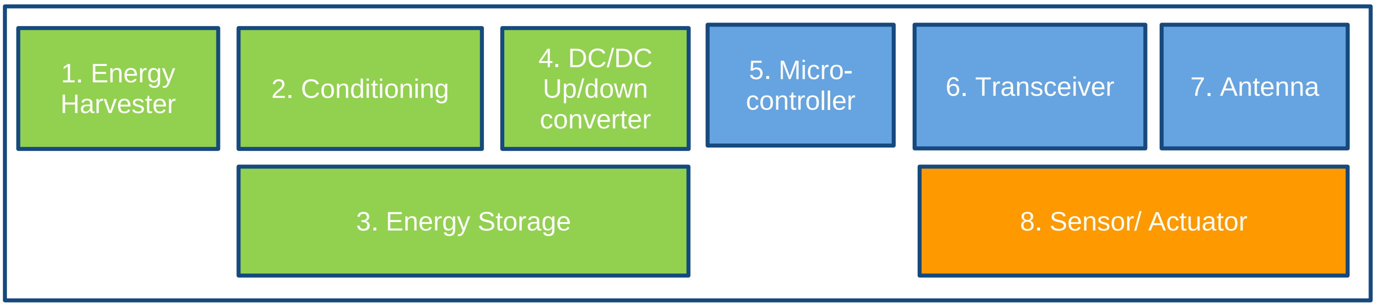
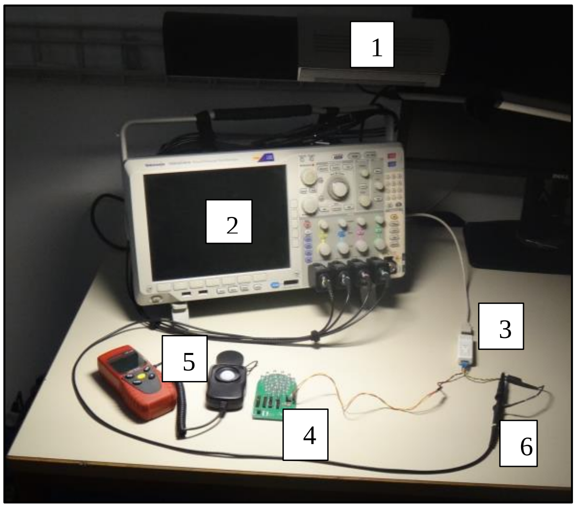
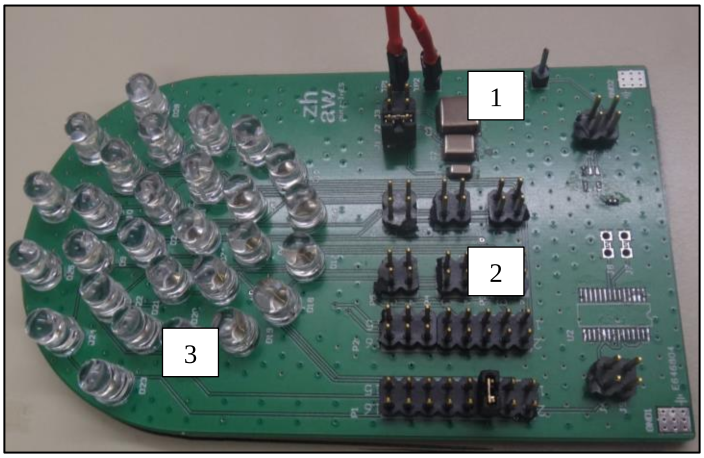


Fig. 1. Block diagram showing the different part of a Wireless embedded system powered with harvested energy



1. Light source
2. Scope
3. High impedance adapter
4. LEDs + storage board
5. Lux meter
6 Scope probe

Fig. 2. Setup for measuring the harvested energy



1. Capacitors used as storage elements. Jumpers are used to make a selection
2. Jumpers used to connect LEDs
3. LEDs

Fig. 3. LED board for experimenting with different configurations

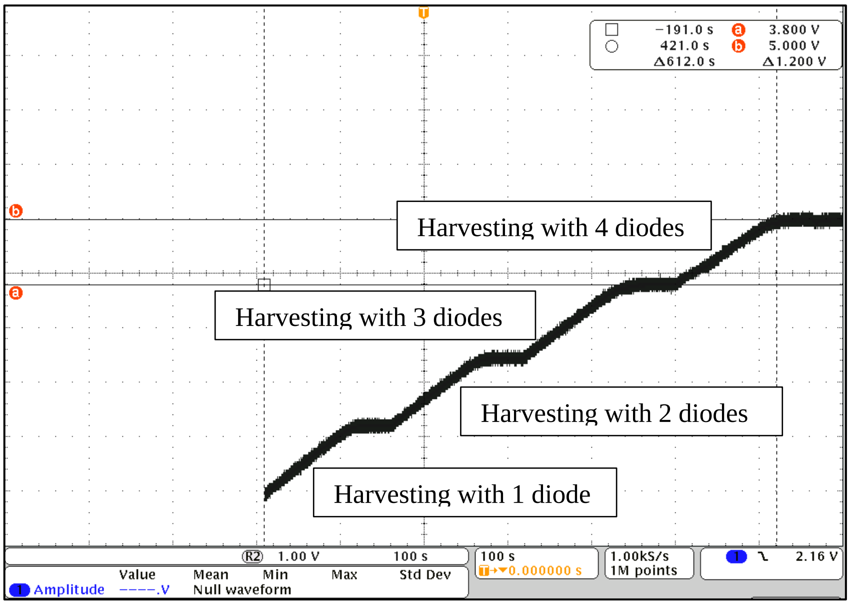


Fig. 4 Example of harvesting with 1,2,3,4 diodes in series. Diodes are introduced in series one after the other.

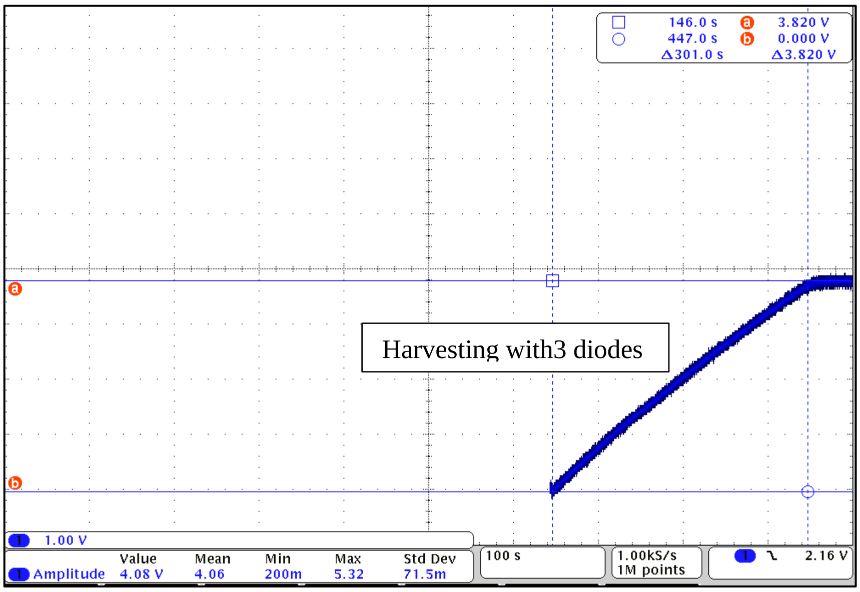
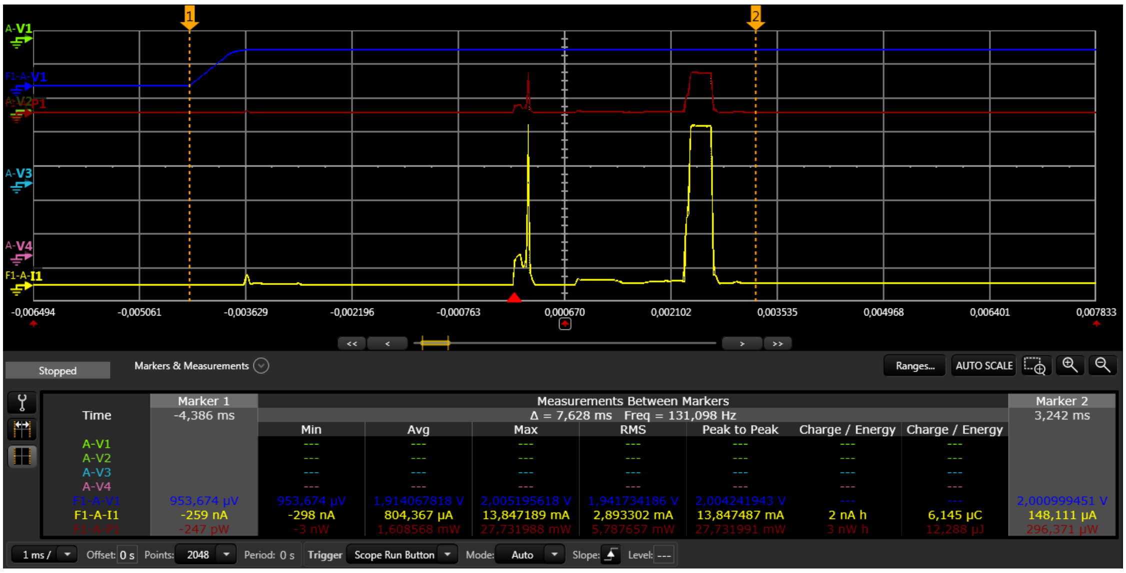


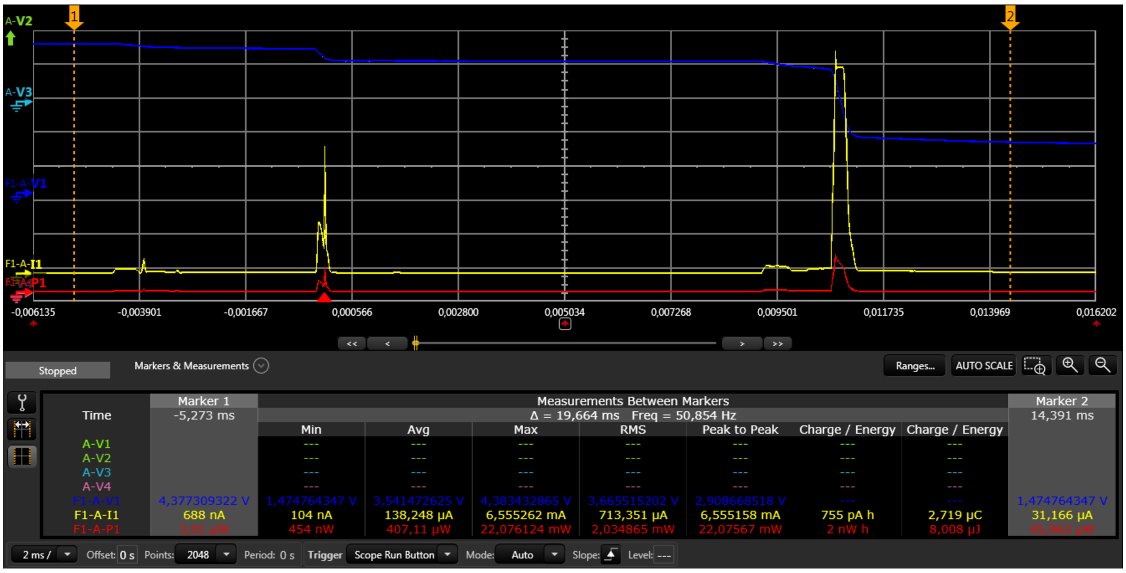
Fig. 5. Example of harvesting with 3 LEDs in series from the start



Time	Marker 1	Measurements Between Markers							Marker 2
	-4,386 ms	Δ = 7,628 ms Freq = 131,098 Hz							3,242 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
A-V1		---	---	---	---	---	---	---	
A-V2		---	---	---	---	---	---	---	
A-V3		---	---	---	---	---	---	---	
A-V4		---	---	---	---	---	---	---	
F1-A-V1	953,674 µV	953,674 µV	1,914067818 V	2,005195618 V	1,941734186 V	2,004241943 V	---	---	2,000999451 V
F1-A-I1	-259 nA	-298 nA	804,367 µA	13,847189 mA	2,893302 mA	13,847487 mA	2 nA h	6,145 µC	148,111 µA
F1-A-P1	-247 pW	-3 nW	1,608568 mW	27,731988 mW	5,787657 mW	27,731991 mW	3 nW h	12,288 µJ	296,371 µW

1 ms / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

Fig. 6. Startup + Ble frame with 27 bytes total (Preamble …. CRC). Powered from a PS. Optimal when voltage constant. 1.88 v/div, 3mA/div, 23mW/div 12.3µJ needed



Time	Marker 1	Measurements Between Markers							Marker 2
	-5,273 ms	Δ = 19,664 ms Freq = 50,854 Hz							14,391 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
A-V1		---	---	---	---	---	---	---	
A-V2		---	---	---	---	---	---	---	
A-V3		---	---	---	---	---	---	---	
A-V4		---	---	---	---	---	---	---	
F1-A-V1	4,377309322 V	1,474764347 V	3,541472625 V	4,383432865 V	3,665515202 V	2,908668518 V	---	---	1,474764347 V
F1-A-I1	688 nA	104 nA	138,248 µA	6,555262 mA	713,351 µA	6,555158 mA	755 pA h	2,719 µC	31,166 µA
F1-A-P1	3,01 µW	454 nW	407,11 µW	22,076124 mW	2,034865 mW	22,07567 mW	2 nW h	8,008 µJ	45,963 µW

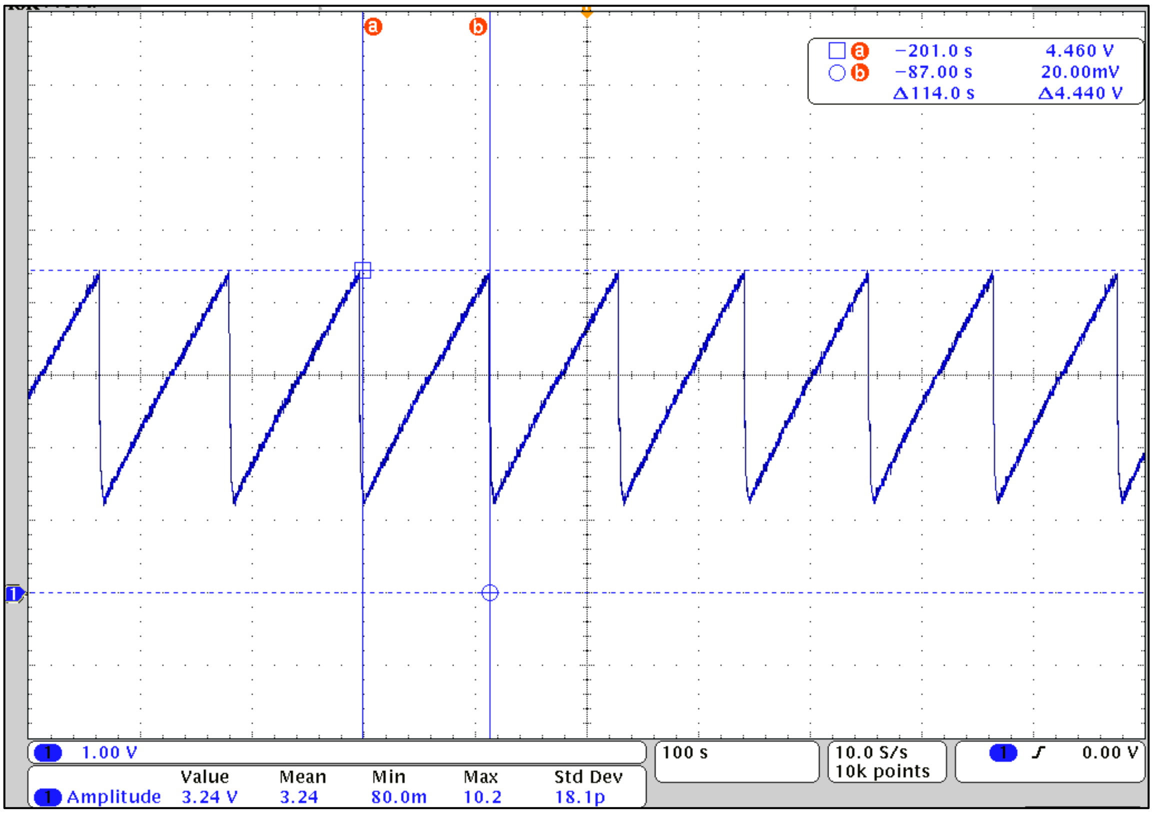
2 ms / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

Fig. 7. 1-2 µF storage in system. Not enough energy for a Ble frame. The frame is wrongly transmitted (last parts truncated because there is not enough energy). But the available energy will be enough for the short frame in the proprietary system.

Time	Marker 1 -5,273 ms	Measurements Between Markers Δ = 19,664 ms Freq = 50,854 Hz Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	Marker 2 14,391 ms
A-V1		---	---	---	---	---	---	---	
A-V2		---	---	---	---	---	---	---	
A-V3		---	---	---	---	---	---	---	
A-V4		---	---	---	---	---	---	---	
F1-A-V1	4,378840446 V	3,710612059 V	4,205984164 V	4,383432865 V	4,211377561 V	672,820807 mV	---	---	3,710612059 V
F1-A-I1	-52 nA	-753 nA	301,499 µA	13,320258 mA	1,548339 mA	13,32101 mA	2 nA h	5,931 µC	123,42 µA
F1-A-P1	-226 nW	-3,296 µW	1,224889 mW	55,696752 mW	6,239811 mW	55,700049 mW	7 nW h	24,095 µJ	457,962 µW

2 ms / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

Fig. 8. 10µF storage. Frame is enough for Ble. 1 ADV sent /1v/div, 2mA/div, 20mw/div). Whole system starts around 4.4V and works down to 3.7 volts. 24µJ measured.



☐ a	−201.0 s	4.460 V
○ b	−87.00 s	20.00mV
	Δ114.0 s	Δ4.440 V

1 1.00 V
100 s
10.0 S/s
10k points
1 0.00 V

	Value	Mean	Min	Max	Std Dev
1 Amplitude	3.24 V	3.24	80.0m	10.2	18.1p

Fig. 9. 10µF storage used, 1000 lux, 4 LEDs in series. The curves show the storage voltage. It is charged to about 4.5 volts. It is then discharged when the load is powered on, sending 3 ADV Ble frames (1 in each ADV channel)
After the first cycle, it takes about 114 seconds to charge the storage to the needed voltage.

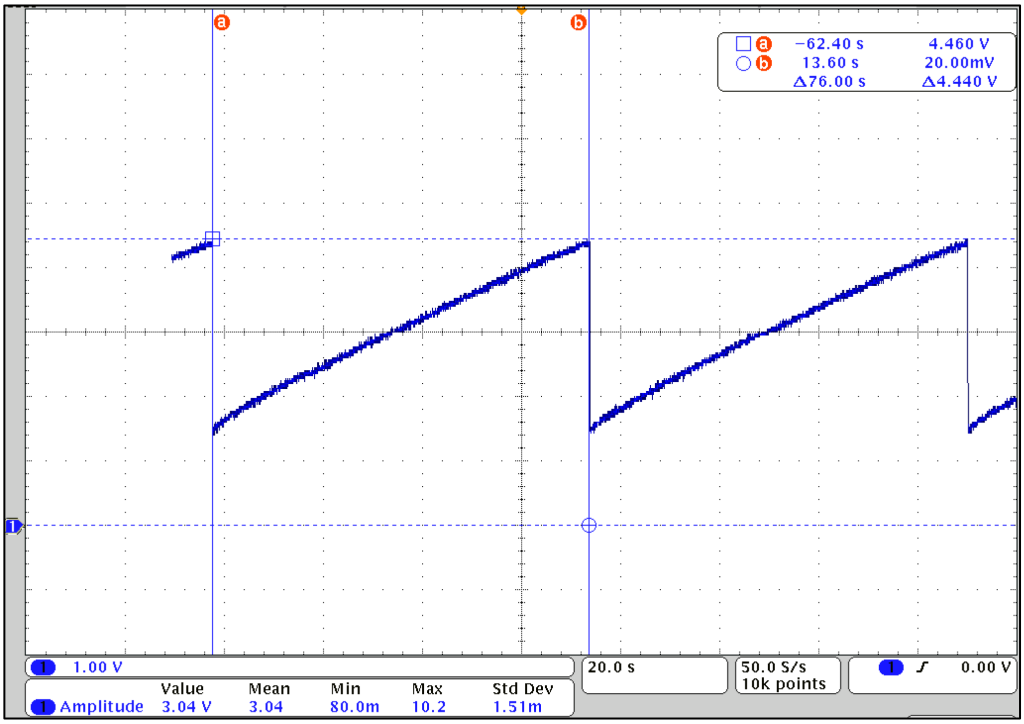


Fig. 10. 1-2µF storage used, 250 lux, 4 LEDs in series. The curves show the storage voltage. It is charged to about 4.5 volts. It is then discharged when the load is powered on, sending 1 proprietary wireless frame.
After the first cycle, it takes about 76 seconds to charge the storage to the needed voltage.

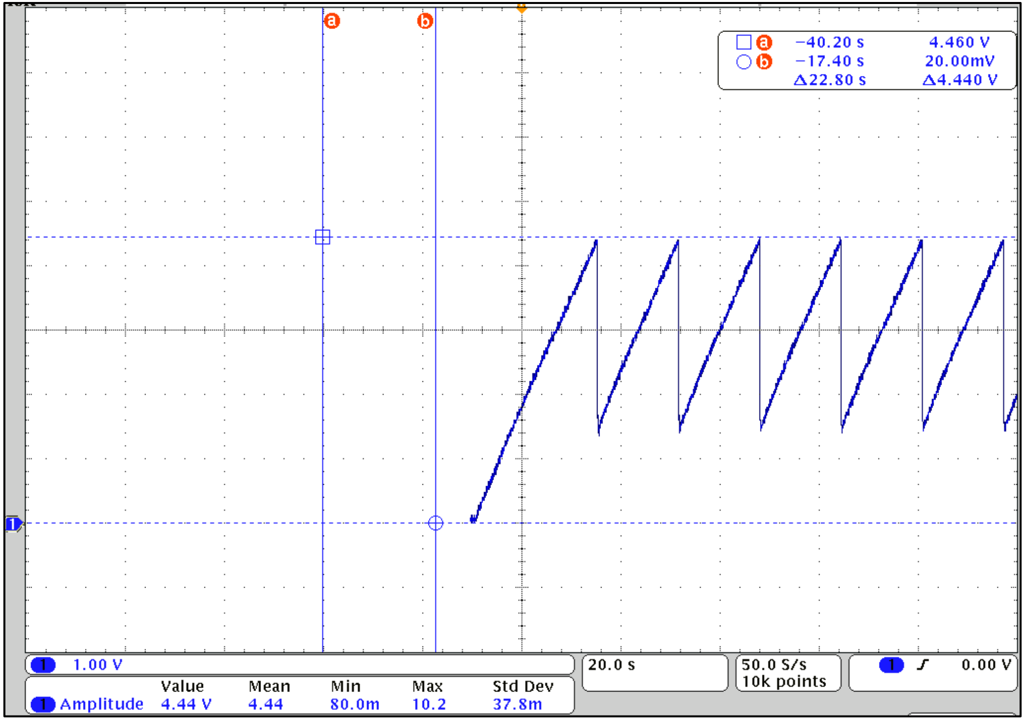


Fig.11. 1µF storage used, 1000 lux, 4 LEDs in series. The curves show the storage voltage. It is charged to about 4.5 volts. It is then discharged when the load is powered on, sending 1 proprietary wireless frame.
It takes about 23 seconds to charge the storage to the needed voltage.

Fig.12. Sensor powered by 4 LEDs sending data to a smartphone

Fig.13. Sensors with different LEDs