Energy Independent Wireless Sensor Network Design

Marin Alexandru-Gabriel
Politehnica University of Bucharest
Bucharest, Romania
marin.alexandru.gabriel@gmail.com

Tudose Dan Stefan
Politehnica University of Bucharest
Bucharest, Romania
dan.tudose@cs.pub.ro

***Abstract*—Battery powered wireless sensor nodes (WSN) are rarely efficient from the point of view of life time, development and maintenance cost. In this context, energy harvesting techniques are used more and more, coupled with supercapacitors, in order to mitigate the costs and increase the lifetime. This paper presents the results of powering Sparrow v3, a wireless sensor node, from supercapacitors charged by a solar panel. The experimental results show that this system may operate in an autonomous mode, using only the power provided by the photovoltaic cells. The novelty of this setup is represented by its small solar panel, combined with supercapacitors which have a smaller capacity than other similar systems. A highly optimized code had to be implemented in order to achieve the energy autonomy goal.**

Keywords—Wireless sensor node (WSN), energy harvesting, solar panel, supercapacitors.

I. INTRODUCTION

The lifetime of wireless sensor nodes is limited primarily by their energy storage device, especially when a battery is used. Batteries have a small and limited number of recharge cycles, leading to the necessity of replacing them after one or two years. Since modern WSN based applications require the deployment of up to thousands of such devices, replacing their batteries at time intervals of a few years would lead to a high cost increase. In this context, substituting the battery with a supercapacitor would represent a good solution, having in mind the WSN's lifetime maximization.

Supercapacitors have some important advantages compared to batteries, like their power density, low equivalent series resistance and low leakage current [1]. But more important, a capacitor's cycle life is much greater than a battery's one, with the former being able to survive to more than 500,000 recharge cycles, while the latter can only be recharged a few hundred times [2]. A disadvantage of supercapacitors is that they have a much smaller capacity than batteries. But this drawback can be mitigated or eliminated by using energy harvesting techniques coupled with energy saving strategies, such as duty cycling. The solution presented in this paper uses both of these methods, with the supercapacitors being recharged by a solar panel, while the WSN is duty cycling, sending messages at time intervals of 1 minute.

II. STATE OF THE ART

Maximizing a WSN's lifetime by using a solar panel together with supercapacitors is a subject of active research nowadays. However, a complete energy autonomous WSN solution where the supercapacitors are recharged by only one solar panel with a small peak power could not be found by the authors of this paper.

Nonetheless, multiple similar projects exist. One of them is Everlast [3], a solar panel supercapacitor charged wireless sensor node. Everlast's energy storage device is represented by a supercapacitor of 100F, which can store an energy equivalent to 300J. This system is equipped with a low power microcontroller, PIC16LF747, characterized by a current consumption starting from 25μA at 31.25 kHz frequency up to 930μA at 8MHz frequency. The transceiver used by Everlast is low power as well - Nordic nRF2401, which can operate at data rates up to 1Mbps, typically consuming 13mA supply current at 3V. Everlast's creators claim that this WSN can operate at a duty cycle of 50% with data transfer rate of 1Mbps for a period of 20 years. The solar panel used to recharge Everlast's supercapacitor has a peak power pf 450mW, which is more than 20 times the peak power of the solar panel used to recharge the supercapacitors of our WSN.

Another example of solar energy harvesting WSN is Solar-Biscuit [4]. It has a hardware configuration which includes a PIC 18LF452 microchip, a 315MHz RF module (ChipCon CC1000) and a temperature and humidity sensor (Sensiron SH11). A 25cm^2 solar panel charges a low internal impedance capacitor (5V, 1F). Solar-Biscuit manages to communicate perpetually if the solar panel provides enough current to the capacitor. On the other hand, when the weather is not sunny enough the Solar-Biscuit system will have to continuously monitor its charge level and send data only when enough power is available, while our WSN is capable of continuous operation for a period of more than 12 days if no energy is harvested by the solar panel.

Sunflower [5] uses four PIN photo diodes to charge a little supercapacitor of 0.2F, being a battery less node like the previous examples. The system uses a 16-bit MSP430 microcontroller from Texas Instruments, MSP430F1232, which needs at least 0.7μA when active. However, multiple Sunflower nodes communicate through wired interfaces, and not by using radio transceivers. The node's lifetime is supposed to be unlimited in this conditions.

III. HARDWARE ARCHITECTURE

The wireless sensor system presented in this paper, shown in Fig. 1, is based on Sparrow v3 [6]. The energy is stored in two supercapacitors of 30F and 2.3V connected in series, forming an equivalent supercapacitor of 15F and 4.6V. Energy is harvested into the supercapacitors by using an IXYS XOB [7] solar panel. Two types of solar panels were used for experimental tests. As we will see in a later section, these two types of solar panels influenced differently the supercapacitor's voltage. Our WSN system has 4.5cm length, 2cm width and 4cm height, being easily portable.

A. Sparrow v3

Sparrow v3 is a WSN equipped with three types of sensors: temperature, relative humidity and ambient light. It has an Atmega128RFA1 [8] microcontroller, which incorporates a 2.4GHz radio transceiver, compatible with IEEE standard 802.15.4, over which the popular high-level communication protocol ZigBee [9] is implemented. However, ZigBee was not used in our project.

ATmega128RFA1 is an 8-bit architecture microcontroller. It has low power consumption (starting from 250nA while in deep sleep; for detailed power consumption levels see Fig. 2), but still offers high computational performance (almost 1MIPS/MHz). On memory terms, it has 16KB of Flash for code download, 4KB of EEPROM and 16KB of RAM. Moreover, ATmega128RFA1 operates at CPU speeds up to 16 MHZ and at voltages between 1.8V and 3.6V.

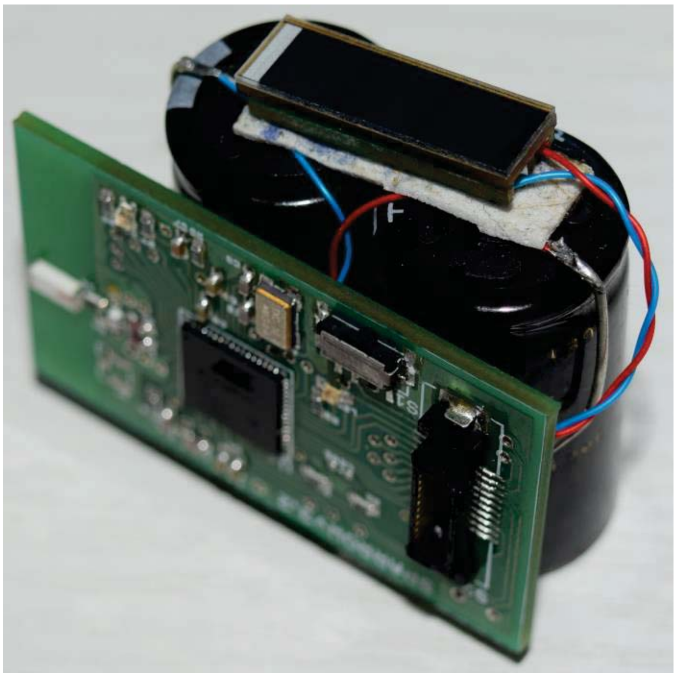

Fig. 1. Wireless sensor node based on Sparrow v3

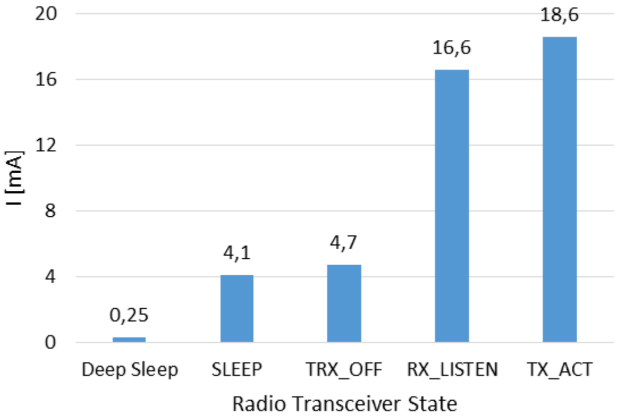

Fig. 2. Atmega128RFA1 power consumption

B. XOB solar panels

IXOLAR SolarBITs are solar cells produced by IXYS. Weighting 0.5 grams and occupying a total surface of 1.54cm^2, these solar panels suit well with the goal of having a self-powered WSN of small size. According to the datasheet of this product, the cell efficiency is typically 17%. Furthermore, SolarBITs may be connected in series, parallel or a combination of these two connection types. In the system presented in this paper, though, only one solar panel per WSN is used.

There are three different SolarBITs available with different voltage and current output. From three types of XOB17 solar panels, only two were used in experimental tests presented later in this paper: XOB17-12x1 and XOB17-04x3. In Table I we present these panels' characteristics. We shall see how both of these solar panels behaved in different lightning conditions.

C. Charging supercapacitors from solar panel

We must have two things in mind when charging supercapacitors from solar panels. First of all, the voltage generated by the photovoltaic cells is most of the time smaller than the supercapacitors voltage. In order to be able to charge in this conditions, a step-up DC to DC converter will be needed, his role being to increase and regulate the small voltage it receives at input. Second of all, a diode or something similar to a diode will be needed to prevent the supercapacitor to discharge. There are DC to DC converters on the market characterized by a low leakage current, so a diode may be unnecessary if such a component is used. In Fig. 3 you can see the solution chosen to achieve the above mentioned goals for the system presented in this paper.

TABLE I. XOB17 SOLAR PANELS CHARACTERISTICS

Type	Open Circuit Voltage [V]	Short Circuit Current [mA]	Typ. Voltage @ Pmpp [V]	Typ. Current @ Pmpp [mA]
XOB17-12x1	0.63	42.0	0.51	39.0
XOB17-04x3	1.89	12.6	1.53	11.7

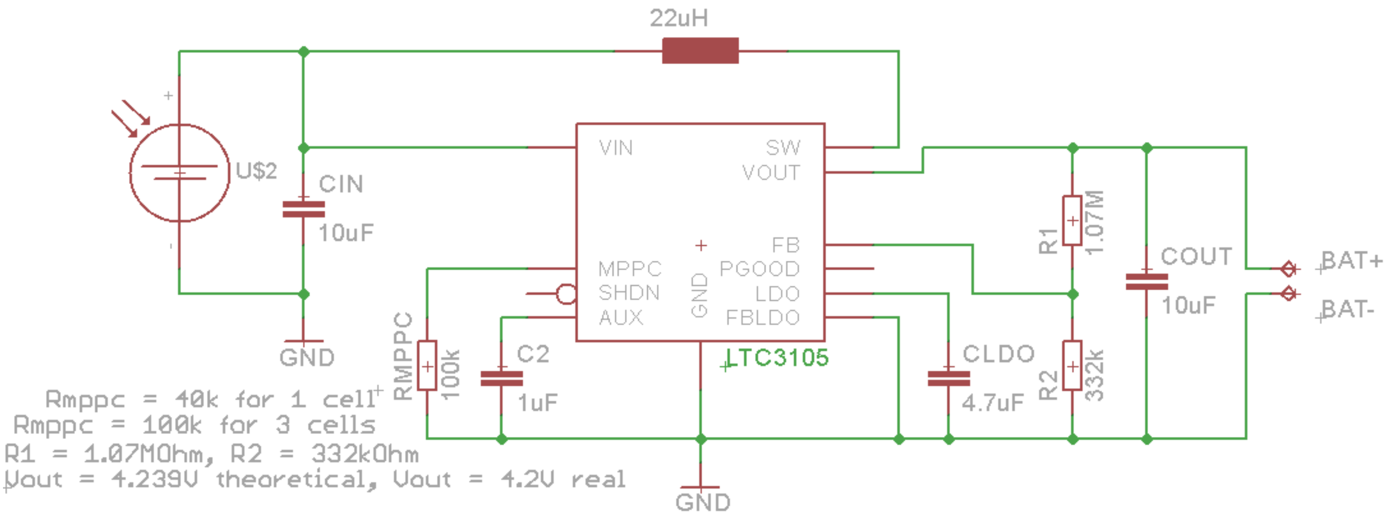

Fig. 3. Eagle scheme of the circuit placed between the solar panel (left side of the circuit) and supercapacitors (right side of the circuit)

LTC3105 [10] is a DC to DC converter produced by Linear Technology, characterized by a start-up voltage of 250mV. It is equipped with a maximum power point control (MPPC), being designed, according to its datasheet, for applications like solar powered supercapacitor chargers, low power wireless communication and energy harvesting.

When LTC3105 is in shutdown mode (because either the voltage produced by the solar panel is too small to enable operation, either the regulated voltage is smaller than the supercapacitor's one), its leakage current is negligible (a few microamperes). As a consequence, we chose to not add a diode into this circuit, since it wouldn't have bring a significant improvement from the point of view of leakage current.

D. *SHT21 – Humidity and temperature sensor IC*

SHT21 [11] is a relative humidity (RH) and temperature (T) sensor produced by Sensirion. Its power consumption varies from 0.15µA in sleep mode to 0.33mA when measuring. If SHT21 is not processing a measuring command, it enters in sleep mode. This sensor's accuracy tolerance is ±2 percent for RH and ±0.3 Celsius degrees for T.

The communication with the sensor is made through I2C, in hold master mode, or in no hold master mode (for ATmega128RFA1, the I2C is represented by the TWI - two wire interface). Using this serial interface, other than reading sensor data, one could modify the user register, updating the RH/T measurement resolution. As it can be seen in Table II, there are multiple resolutions for RH/T measurement - the greater the resolution, the greater the measurement time and the measurement precision. Table II reveals also the maximum measurement time differences for each resolution. These differences are important, because they impact greatly our WSN's lifetime if the master hold on read mode is used. Furthermore, these maximum values must be used as minimum waiting times in communication (if reading SHT21 data asynchronously, one should wait at least the maximum measurement time before reading the measurement result).

TABLE II. MEASUREMENT TIMES FOR RH AND T MEASUREMENTS AT DIFFERENT RESOLUTIONS

Resolution	RH max [ms]	T max [ms]
14	-	85
13	-	43
12	29	22
11	15	11
10	9	-
8	4	-

IV. SOFTWARE ARCHITECTURE

The code for this project was developed in C language only, using Arduino IDE as development environment. If some changes are made to default Arduino IDE layout, Sparrow v3 can be programmed using the mentioned IDE through a bootloader written previously in its flash memory, similar to Zigduino [12].

The network topology used in experiments is formed by a gateway node, which listens permanently for packages, and two other nodes that read data from sensors at fixed time intervals, send them to the gateway through radio and then enter in a deep sleep state, in order to save as much energy as possible. The gateway node is the only one that receives packages, there is no communication between non-gateway nodes. Furthermore, the gateway waits to receive a complete package from one of the nodes, this event being signaled by a TRX24_RX_END interrupt. In this interrupt's handler the package integrity is checked, then, if everything is ok, the message is parsed. As it can be seen in Fig. 4, our typical message contains fields for message size, sender address, sequence number, data read from sensors (temperature, relative humidity, light, power supply voltage) and a CRC, totalizing 13 bytes.

size	address	seq_nr	temp	humid	light	volt.	crc
8bits	16bits	32bits	8bits	8bits	8bits	8bits	16bits

Fig. 4. 13 bytes message format

The gateway sends on a serial interface all the messages it receives from other nodes, in order to facilitate the data monitoring through a serial terminal.

As we mentioned previously, except for the time in which they send data from sensors to gateway, the nodes stay in a deep sleep state. In order to get out of this state we use a timer interrupt together with MAC symbol counter. This interrupt is triggered when the Symbol Counter register has the same value as Symbol Counter Output Compare register. In order for this scenario to work, Symbol Counter Output Compare register must be initialized before entering the deep sleep state with a value correspondent to the deep sleep period wanted.

V. EXPERIMENTAL RESULTS

Two different solar panel models from IXYS have been used for experimental tests: XOB17-12x1 and XOB17-04x3. Furthermore, four types of tests were run: one set to see how each panel type charge the supercapacitors in presence of halogen lamp generated light; a second set to reveal what is the discharge rate when the solar panels provide no voltage; a third set that shows how SHT21 settings influence the discharge rate; a last test which shows that our WSN may run indefinitely if exposed to a few tens of minutes of sun light each day.

A. *Charge rate with constant light provided by halogen lamp*

Experimental results show a significant difference between XOB17-12x1 and XOB17-04x3 regarding the charge rate when the irradiance increases. As it can be seen in Fig. 5 and in Fig. 6, the charge rate increases almost directly proportional with the irradiance when XOB17-04x3 is used, but XOB17-12x1 does not exhibit the same behavior. Instead, XOB17-12x1 seems to produce better results with an irradiance below 12000 lux.

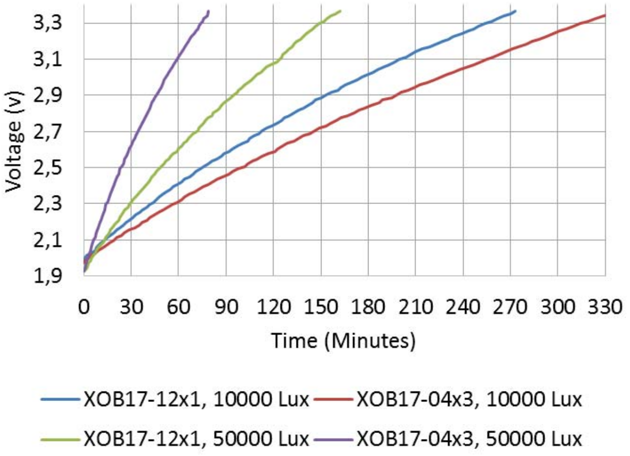

Fig. 5. XOB17-12x1 and XOB17-04x3 charge rates while sending 13B messages - light of 10000 Lux and 50000 Lux

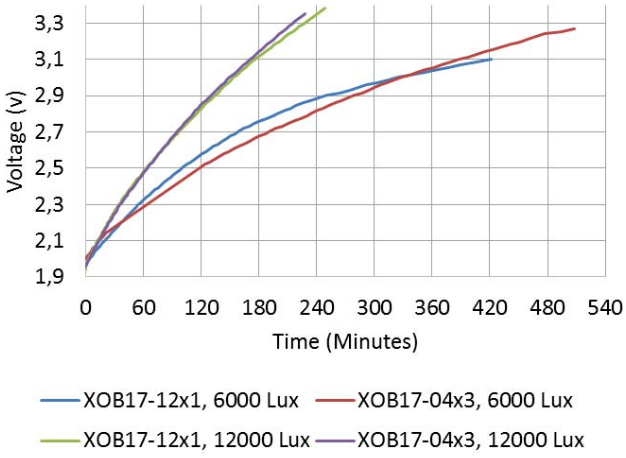

Fig. 6. XOB17-12x1 and XOB17-04x3 charge rates while sending 127B messages - light of 6000 Lux and 12000 Lux

B. *Discharge rate with no photovoltaic charge*

As it can be seen in Fig. 7, the discharge rate is generally linear throughout the voltage range at which the system was tested: 3.34V – 1.98V. However, at the high end of this range, between 3.34V and 3.25V, a nonlinear discharge rate can be observed. This behavior can be viewed in Fig. 8.

There are multiple factors which influence supercapacitors discharge rate. The most important of them are: the leakage current when the microcontroller is in deep sleep state, the current needed for sending a message, the frequency at which the messages are sent and the current needed for reading data from sensors.

Even though one would expect the discharge rate to decrease more or less directly proportional with the frequency of messages, this does not happen. This behavior can be seen when comparing the discharge rates from Fig. 7 and Fig. 8. In Fig.8 we can see that when sending twenty messages of 127 bytes per second the voltage drops from 3.3V to 3.2V in approximately 20 minutes. The same voltage drop is met in an interval of 220 minutes when sending one message of 127 bytes per second, an interval that is only eleven times bigger than the previous one, even though the message frequency decreased twenty times. When sending the same 127 bytes message with a one minute frequency, the same 3.3V to 3.2V voltage drop is encountered in an interval of almost 480 minutes, which is twenty four times bigger than the interval of the first mentioned test. However, in this latter case the message frequency was reduced 1200 times compared to the test in which we sent 20 messages per second.

We may explain why the discharge rate is not directly proportional with the message frequency by taking into account the leakage current. Furthermore, the timer we mentioned in the Software Architecture section is enabled even in deep sleep, consuming some power as well. We measured a total current consumption of 13µA when the ATmega128RFA1 microcontroller is in deep sleep (leakage current plus timer consumption).

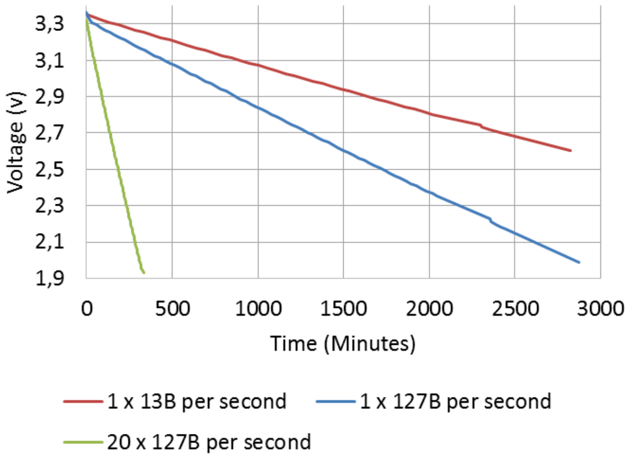

Fig. 7. Discharge rate with no solar panel charging - linear behavior

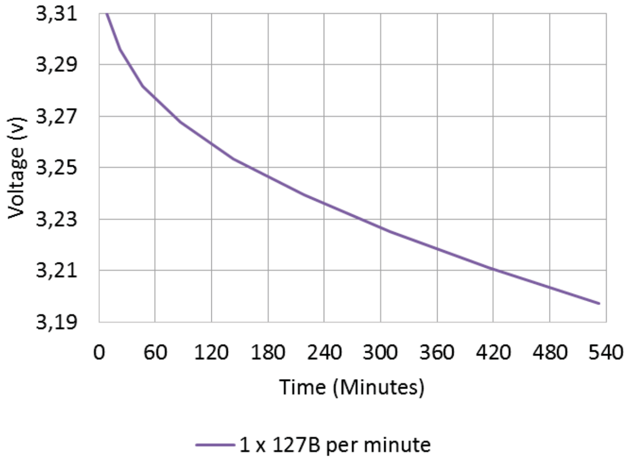

Fig. 8. Discharge rate with no solar panel charging – non-linear behavior

C. *Discharge rate with different SHT21 reading*

The experiments shown that the manner in which data is read from SHT21 has a great impact over WSN's lifetime. This can be observed by reading data in the following four ways:

a. Default resolution of 12/14bit for RH/T and I2C hold master reading mode (worst impact over WSN's lifetime)

b. Change resolution to 8/12bit for RH/T and no I2C hold master reading mode (least impact over WSN's lifetime)

c. Default resolution of 12/14bit for RH/T and no I2C hold master reading mode (impact over lifetime somewhere between read mode a and read mode b)

d. Change resolution to 8/12bit for RH/T and I2C hold master reading mode (impact over lifetime somewhere between read mode a and read mode b, but worse than read mode c)

Fig. 9 shows that in worst case scenario, represented by default SHT21 resolution and with master hold on I2C reading, the discharge rate is six times higher than that observed when SHT21 is set to minimum resolution coupled with master hold off I2C reading.

Master hold on reading mode means that the I2C bus is kept busy until the measuring is over. The serial clock line is blocked while measuring. In the no master hold case, the serial clock line is free, i.e. while the sensor is measuring, the serial clock line may be used for communicating. This is similar to the comparison of synchronous and asynchronous calls.

For the best case scenario we sent a command of asynchronous measurement to SHT21. Based on the values provided in Table II, the microprocessor was put into a deep sleep state for a period equal to the maximum measurement time for the chosen minimum resolution (8/12bit for RH/T). When the microprocessor was "awaken" from its deep sleep by the symbol counter interrupt, the sensor was ready to answer to the previously sent command.

The settings of default SHT21 resolution and master hold on I2C reading mode represent the worst case scenario for the discharge rate because of two reasons. First of all, master hold on mode is the equivalent of synchronous command. The microprocessor must wait in a busy loop until the sensor finish its measurement. We already saw in Fig. 2 that at least 4.7mA are consumed by Atmega128RFA1 in a non-sleep state, versus only 250nA in deep sleep. Secondly, the default resolution is the one which requires the biggest wait times until the measurement is over.

Another thing that could impact a WSN's lifetime is the length of the period between power-up time and the moment when the sensor is ready to receive commands from the microcontroller. According to its datasheet, SHT21 needs at most 15ms to be ready. If the microcontroller is not put into power save mode in this interval, the discharge rate would accelerate. As a consequence, we used a SHT21 pre-wakeup phase in order to save energy. This phase requires waking up 15ms earlier, turning SHT21 sensor on, and then going back into power save mode for 15ms. When this time slot expires and the microcontroller exits the power save mode, SHT21 is ready to receive commands.

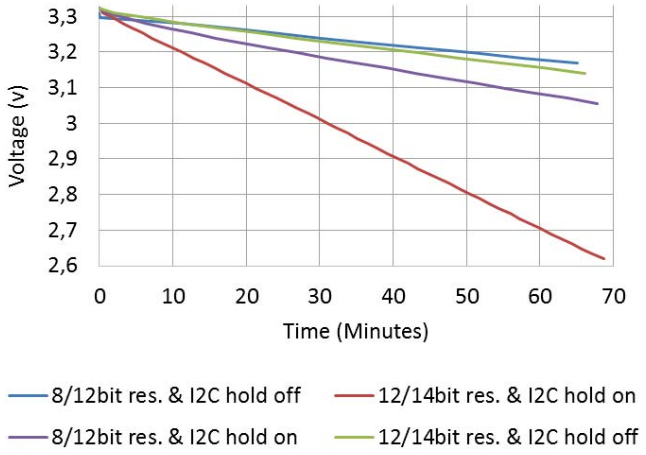

Fig. 9. Discharge rate with different SHT21 reading; 127B sent once per 0.25 seconds

D. *Continuous running simulation*

If powered on with the supercapacitors at 3.3 volts, the wireless sensor node presented in this paper could operate for approximately 12 days sending messages of 13B every minute, without being charged by the solar panel in this time. This means a daily voltage drop of roughly 0.11 volts. At the end of twelfth day it will eventually run out of power, when the supercapacitors voltage will drop to approximately 1.98 volts, as the tests showed that below this voltage it will not be possible to read data from SHT21. Furthermore, at 1.92 volts, there will not be enough power for the radio transceiver to properly send a message.

Based on the charging rates presented in Fig. 5 and Fig. 6 and based on this study [13], in order to operate continuously, sending 13B per minute, our system will need at least 21 minutes of full daylight if XOB17-12x1 is used and at least 26 minutes of full daylight if XOB17-04x3 is used. By full daylight we understand a light of 10000Lux, available in a sunny day, but with no direct sun exposure. Furthermore, in case of direct sunlight with illuminance of at least 50000Lux, 12 minutes of exposure will suffice to charge the supercapacitors with a full day supply in case of XOB17-12x1 and 6 minutes will be enough for XOB17-04x3 to reach the same goal.

Fig. 10 presents the results of monitoring the supercapacitors voltage for a period of four days, period in which we exposed an XOB17-12x1 solar panel once per 24 hours to a 10000Lux light, generated by a halogen lamp. The exposure time was near the estimated 21 minutes needed for harvesting energy with XOB17-12x1 from a 10000Lux light, in order to achieve continuous operation. We observed that the energy harvested in these 21 minutes is enough for 24 hours WSN operation.

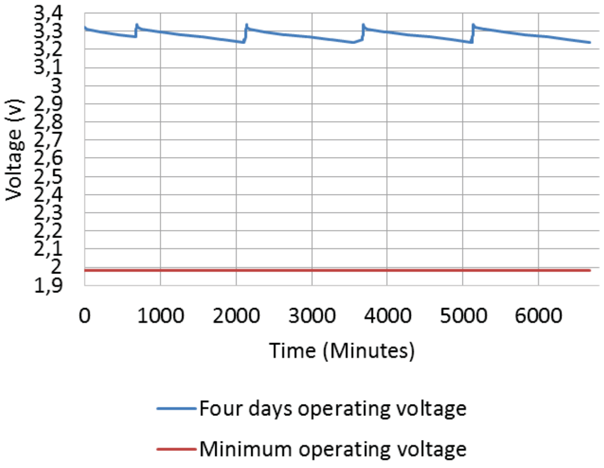

Fig. 10. Four days voltage monitoring; 13B sent once per minute; 10000Lux exposure once per 24 hours; Exposure time of maximum 21 minutes

VI. CONCLUSIONS

This paper showed that the concept of a completely self-powered, continuous operating and small sized WSN is feasible even when the harvested energy is not as much as other similar systems need. Moreover, the life time of the system presented here is greatly increased by using supercapacitors as energy storage devices, in detriment of conventional batteries, characterized by a much smaller number of available recycle cycles.

Measuring 4.5cm length, 2cm width and 4cm height, our WSN is capable of 12 days continuous operation if no energy is harvested in this interval. Furthermore, it needs less than an half of hour of daylight exposure daily for “infinite” lifetime. In this conditions, we may conclude that our system will operate uninterruptedly as long as the supercapacitors will survive. Although we did not present in the current paper any results of exposing our WSN system to an illuminance lower than 6000Lux, we estimate that it will be possible to operate continuously even with less light. This makes our WSN suitable not only for outdoor monitoring projects, but for indoor monitoring as well.

Another result of this research is represented by the discovery that the manner in which data is read from sensors can greatly impact a WSN system’s lifetime. Different modes of reading data from SHT21 leaded to discharge rates where the best case scenario used six times less energy than the worst case one.

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