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Abstract—Emerging technologies for ambient energy harvesting have enabled the development of Energy-Harvesting Aware Wireless Sensor Networks. This paper presents a new energy efficient approach for the characterization of a system composed of a solar mini-panel and supercapacitors (supercaps) that is able to supply energy to the sensor node from the three possible sources, namely, the supercapacitor (supercap), the backup battery and the solar-panel itself. Besides the efficiency this approach preserves the integrity of the supercapacitors, avoiding the real risks of degradation usually found in the literature. It is also shown that the energy efficiency provides not only energy awareness sensor nodes, but also information for the analysis and planning of QoS metrics for Wireless Sensor Networks.

I. INTRODUCTION

A Wireless Sensor Network (WSN) is composed of many autonomous and compact devices called sensor nodes. They have limited resources, such as computational capacity, memory, communication, and energy. In most applications, Wireless Sensor Networks (WSNs) will deploy a large number of distributed sensor nodes in remote or inhospitable places, making batteries their main source of energy. While computer processor speed and memory capacity have exhibited magnitude orders of increase since 1990s, the battery energy density has only tripled, that is, the energy supply and storage technology is not advancing at the same rate [1]. Due to the limited capacity of batteries and difficult replacement or recharging, energy becomes the most precious resources of WSNs.

In this context of limited resources it is necessary to design all the network components, from the node’s hardware to the protocols, in order to obtain the minimum possible power consumption in an efficient way. Despite all the research attention received in the power optimization area, the problem of extending the lifetime of a WSN is still under investigation, specially when moving from the laboratory environment to real applications [2].

Emerging technologies for the capture of environmental energy are being proposed to solve the scarcity supply of energy for WSN. The capture of solar energy using solar panels composed by photovoltaics cells provides the most dense power source [3]. However, the characterization of power system found in the literature composed of mini solar-panels and a primary storage device (secondary battery or supercapacitor) provides either a low efficiency or a high level of degradation on the storage components, since they use a NiMH battery to set the operating point of the solar panel [3], forcing the batteries to daily recharge cycles and consequently degrading their lifetime, or use supercapacitors that sets the operating point where the solar panel will not supply enough current to power autonomously the WSN node [4]. Moreover, it will be shown that for actual WSN node duty cycles (specially at 1%) the operating voltage is superior to the maximum voltage for supercapacitors, which drastically reduces their lifetime. Figure 1 shows this technique.

![Fig. 1. Usual technique for environmental harvested energy.](image)

This paper focuses in presenting a novel energy-efficient power system composed of a mini solar-panel, supercapacitors, rechargeable batteries and a management unit. In this way the node will have three distinct sources of energy: a primary storage device (the supercapacitor), a secondary storage (the secondary battery, as backup) and the mini solar-panel. Figure 2 shows this new approach, where three, and not the usual two, sources of energy power the node.

The presented solution enables the development of energy-
II. SOLAR PANEL - SUPERCAPACITORS SYSTEM

This section presents a description and analysis of the components of an energy capture module, such that a proper characterization of the energy efficiency is obtained and a hardware implementation is realized. The objective is the development of a more efficient solar energy capture module that enables solar energy aware WSN nodes [3] with higher transmission power, larger duty cycles and the possibility of QoS metrics analysis and tests.

A. Solar panel characteristics

Solar energy is the most abundant and accessible source on environmental energy. An important aspect of photovoltaic cells used to convert solar to electrical energy is conversion efficiency around 18% for commercial solutions. However, recent developments promises efficiency above 40% [7], making it an attractive energy-harvesting source for WSNs.

The solar mini-panel SCC3766 from Solarbotics [8] was chosen due to its commercial availability, low cost, and supply current adequate to WSN nodes (20-30 mA). SCC3766 is a series of small-scale, high voltage, epoxy-encapsulated polycrystalline solar cells. Epoxy protects the 14 cells mounted on a PCB backplane, making them very robust. Nominally rated at 6.7 V and 30 mA, manufacturer’s direct-sunlight tests show just over 8 V open-circuit, and 44mA short-circuit.

The V-I curve of the SCC3766 solar panel is presented in Fig. 3, and shows that it behaves like a voltage-controlled current source. The setting point is defined by the designer according to the system’s operating point. This current source behavior disables direct supply to the load (sensor node), since the voltage becomes dependent of the load impedance variation. This imposes the use of a primary storage device which function is to store the energy captured by the solar mini-panel and supply a stable voltage level to the load.

Thus, there is an optimal operating set point, in which the power from the mini-panel is maximized, that must be set based on the primary storage devices (in this work supercapacitors) and the demanded current requirements (sensor node and backup secondary battery recharge currents). Since the energy stored in the supercapacitor depends on the voltage level \( \frac{1}{2} CV^2 \), and the typical sensor node current is about 20-30 mA, the solar mini-panel set point is found by the highest possible voltage level (to store the maximal amount of energy on the supercapacitors) and the largest current (load requirements). For this solar mini-panel’s V-I curve the optimal set point is (4 V, 40 mA).

B. Supercapacitors characteristics

Rechargeable batteries support a few hundred recharge cycles. For example, Lithium-Ion and NiMH supports at most 500 cycles. When submitted to frequent recharge cycles, like the solution in [3], their lifetime are significantly degraded and the power module will not provide energy for a period of several years, as expected.

Supercapacitors, also known as ultra-capacitors or double-layer capacitors (DLC), are an emerging device for energy storage with a higher power density than batteries and 10 to 20 times that of regular electrolytic capacitors [9]. They can be charged and discharged continuously without degradation and are ideal for pulsating applications, such as the typical WSN. Their disadvantage, compared to batteries, is a higher leak current, larger size and cost.

The proposed solution uses a carbon aerogel supercapacitor from PowerStor [10] that present a very high energy density (100 times that of electrolyte caps) and power density (10 to 100 times that of batteries) [10]; equivalent series resistance (ESR) extremely low compared to activated carbon supercaps; relative low leak current; ample operating temperature range; and may be recharged hundred thousand times.

Considering a duty cycle typical to WSN of 1%, an active node current of 20 mA and a sleeping current of 5\( \mu \)A, the average current is \( 0.01 \times 20 \text{ mA} + 0.99 \times 5 \text{ } \mu \text{A} = 0.205 \text{ mA} \). The sensor node operating voltage is 3.6 V and the supercaps will power for 10 hours (estimated period without sun light). Filling the spreadsheet "PowerStor Aerogel Supercapacitor" [11], and using the leak current provided by [4], two supercaps
of 22 F / 2.5 V each in series will be used, providing the 3.6 V and minimizing the leak current.

C. Hardware implementation

The proposed power system management unit for solar mini-panel and supercapacitors is depicted in Fig. 4.

In the middle of the diagram there is a 100 ohms resistor connected to an amperemeter used to emulate a charging battery, but can also be used to emulate an increase of power consumption as in an increased transmission power. To emulate the sensor node, another resistor located at the right side is connected to a transistor that provides a switch to turn on and off the load. Its base terminal is connected to a microcontroller that synthesizes a square wave to create a programmable duty cycle.

In the left side of the diagram the solar mini-panel and the supercapacitors are located, along with components used to set the operating point. The supercapacitors are connected to 1MΩ resistors in parallel, and the two in parallel to the output of the mini-panel. Those resistors act as a voltage divider reducing to an acceptable voltage for each supercap. They also balance each capacitors’ voltage, since they may have different capacitances and one may exceed the operating voltage (above 2.5 V). This procedure is necessary since they exhibit a tolerance of ± 20%. To avoid lifetime degradation, due to reverse current flowing through the photovoltaic panel, a schottky diode (D1) with a direct voltage drop of 0.25 V is used in series with the mini-panel. To set the voltage operating point (3.3 V - 4.0 V), and also guaranteeing energy efficiency and lifetime, a zener diode (D3) of 3.6 V is used and becomes a key element in this circuit.

Under critical operating conditions, such as a cloudy day, the supercaps supplies the energy to the sensor node. Diode D2 avoids that the zener diode operates as a load to the supercaps and deviates current from the load. In spite of power dissipation on the zener it will be shown that this consumption is compensated by the autonomicity of the proposed approach. Given the compatibility limitations between the solar mini-panel and the supercaps voltages, the zener diode, in an autonomous and free of software control manner, guarantees that voltage will never be exceeded.

III. Characterization of Solar Panel - Supercapacitors System: Experiments and Results

In order to verify the behavior and characterize the mini-panel/supercap sub-systems and the overall approach, several experiments were performed.

In the first experiment the hardware implementation was built without diodes D2 and D3 and the load, i.e. without any kind of regulation. Figure 5 shows the results for the voltage and current on the supercaps.

These results show the inefficiency of the supercaps to set an optimal operating point for the system. It should be noted the high risks of degradation since while there was solar energy hitting the mini-panel, the supercaps were continuously charged and the voltage crossed the limit (5 V) for both supercaps. At this point the experiment was stopped. If we consider the test curve from the mini-panel manufacturers, the supercaps would charge until 6.7 V, when the current would reach zero amperes and the charging process would stop. However, at this potential the supercaps would rapidly degrade or may even explode.

In the second experiment the zener diode (D3) and diode D2 were connected to the circuit, but the load was still not connected. In order to verify the proposed solution under different level of solar intensity, an ordinary 100 W lamp with varying distance to the mini-panel was used. The lamp was positioned at different distances to provide currents with increasing steps of 5 mA up to the mini-panel limit of 44 mA. In this way it was possible to acquire the characteristic curves as shown on Fig. 6.

As one can see for each current supplied, the supercaps are charged and the zener diode turns on and start to draw part of the current from the supercaps, and even all the current, when the voltage across them is equal to the zener voltage (with an admitted tolerance of 20 %). Since this experiment covered all the mini-panel’s operating range, it can be stated that the voltage will never exceed the 5 V level. Better yet, the operating point will always be in the optimal range of 3.3 V - 4.0 V (Fig. 3), and according to the graphics a range of...
3.4 - 4.3 V. Besides, setting the operating point is performed automatically without the intervention of the node’s processing unit.

In the third experiment, the lamp was positioned at a proper distance providing a steady supply of 35 mA from the solar panel, the switching load was driven with a square wave to the transistor with varying duty cycles of 100%, 50%, 20%, 5%, 1%. In all runs the load on-time, \( t_{ON} \), was 1 second. All scenarios produced very similar results and Fig. 7 presents the results for a typical WSN duty cycle of 1%.

In this experiment, until Time=2,000 seconds the load was disconnected, letting the supercaps to charge up to 4.18 V with an average current of 34.8 mA supplied by the mini-panel. When the load is connected, the voltage on the supercaps stabilizes at 4.17 V. In other words, the solar mini-panel starts to operate autonomously, supplying the load and replenishing the supercaps. However, with a duty cycle of 1%, part of the current supplied by the mini-panel (\( \approx 30 \) mA) is deviated to the zener diode keeping the voltage below the operating level (5 V). Even though this harvested energy is wasted the proper operation of the supercaps is preserved. This extra energy could be used to recharge the backup battery, to increase the transmission power, to increase the node’s duty cycle, or to adjust parameters that make it possible to implement energy-aware WSN [5] and to provide data to improve the analysis and planning of quality of service metrics [6].

The other runs with duty cycles of 5%, 20%, 50% and 100% showed very similar results with minor variations on the average final voltage level between 4.13 V and 4.17 V. A similar behavior regarding the zener current was noticed.

Finally, the last experiment verified the behavior under a critical load, e.g. continuous current flow that emulates a battery recharge, with a constant load (the fixed resistor of 100 \( \Omega \) was connected), and the switching load with a duty cycle of 1 % were applied with fully charged supercaps. Fig. 8 shows the results.

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The voltage on the supercaps stabilizes at approximately 3.445 V, a level still enough to power the loads. Initially most of the current flows through the zener, but when a constant load plus the switching load are connected the current now flows to the loads, confirming that it is possible to use the extra energy obtained during extra sun light to power the node beyond the autonomous operation of the solar mini-panel power module. As long as there is solar energy over the solar mini-panel enough to power at least the node, the resulting energy is composed by the following components: energy supplied by the solar mini-panel, energy stored at the supercaps, and energy stored at the backup battery.

Another run with only the switching load was performed, and the results were quite similar with the final voltage level of 3.476 V.

IV. CONCLUSION

A new approach to an energy-efficient characterization of a solar mini-panel and supercapacitors power module for Energy-Harvesting Aware WSNs was presented. This solution provides energy from supercapacitors, backup batteries and
even energy directly from the solar mini-panel to power the sensor node. Besides energy efficiency, this new approach guarantees supercapacitor integrity and a long lifetime, avoiding risks of degradation due to overvoltage. Finally, the available energy-efficiency provides the base ground for the analysis and planning capacity for quality of service metrics for WSN.

ACKNOWLEDGMENT

The authors would like to thank the following sponsor agencies: Fapemig and CNPq.

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